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ISEE-3 ATTITUDE POSTLAUNCH REPORT

Prepared for

GODDARD SPACE FLIGHT CENTER

By

COMPUTER SCIENCES CORPORATION

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ABSTRACT

This document describes the support provided by the Goddard Space Flight Center (GSFC) Attitude Determination and Control Section (ADCS) and its contractor, Computer Sciences Corporation (CSC), during the 6-month period following the launch of the International Sun-Earth Explorer-3 (ISEE-3) spacecraft on August 12, 1978. Results are presented concerning attitude sensor performance, attitude and bias determination, and attitude control system performance. Also included is a record of the implemented commands for the panoramic attitude sensor (PAS) and hydrazine propulsion system (HPS). Detailed descriptions of attitude hardware and software systems are given in References 1 through 3.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure

LIST OF TABLES

Table

SECTION 1 - INTRODUCTION AND SUMMARY

1.1 PURPOSE

This document describes the attitude support provided by Goddard Space Flight Center (GSFC) and its contractor, Computer Sciences Corporation (CSC), during the 6-month period following the launch of the International Sun-Earth Explorer-3 (ISEE-3) spacecraft on August 12, 1978. It summarizes the principal attitude and bias determination results, provides analyses of attitude sensor and attitude control system performances (including calibration factors), and includes a record of the implemented panoramic attitude sensor (PAS) and hydrazine propulsion system (HPS) thruster commands. Detailed descriptions of attitude hardware and software systems are given in References 1 through 3.

1.2 MISSION OVERVIEW

This subsection provides an overview of the major attitude-related events of the ISEE-3 mission from launch through halo orbit insertion.

ISEE-3 was launched from the Eastern Test Range aboard a Delta launch vehicle on August 12, 1978, at 1512 GMT. The spacecraft was injected into a near nominal transfer orbit 59 minutes and 11 seconds after liftoff, and the spacecraft entered sunlight at 1619 GMT. The fine Sun sensors (FSS) were turned on, and the spin rate was determined to be 48.66 revolutions per minute (rpm), which was within the nominal range of 46 ± 5 rpm. The initial panoramic attitude scanner commands were sent at this time, but the PAS mounting angle was seen not to follow the predetermined settings. The cause of the discrepancy has been ascribed to the PAS being commanded in continuous rather than sector submode when in planar mode (Reference 4). The proper commands were subsequently sent but the first attitude maneuver was delayed by approximately 1 hour and 28 minutes to allow the injection attitude to be determined.

Between Injection (I) + 12 minutes (m) to I + 24^m , the yo-yo despin maneuver reduced the spin rate to 10.14 rpm, and the deployment of the inertia and experiment booms lowered the spin rate to approximately 7 rpm. The first spin maneuver took place at 1657 GMT to increase the spin rate to 9.12 rpm. The first attitude maneuver was carried out at 1838 GMT (delayed by 1 hour 28 minutes) to successfully reorient the spacecraft to the orbit normal. This was a 90-degree maneuver which was monitored in real time using the Multisatellite Attitude Determination (MSAD)/ISEE-C system.

A spin maneuver was performed at 2030 GMT which raised the spin rate to 38.68 rpm in preparation for the first orbit maneuver.

The second attitude maneuver was canceled because it was unnecessary.

The first orbit maneuver occurred on August 13, between 1010 and 1110 GMT (see Reference 5).

The attitude was oriented to the North Ecliptic Pole on August 14 at 1010 GMT, with the spin rate still near 38 rpm. On August 15, the X-Y-wire antennas were deployed between 1316 and 1452 GMT, after which the spin rate was trimmed to 19.85 rpm. This completed the launch events.

Attitude determinations were provided once a week thereafter. The PAS/FSS and FSS-only systems were used until the second midcourse maneuver on September 6; the FSS-only system was used thereafter. Poor attitude determination geometry did not allow use of the PAS/FSS system beyond this point.

The second midcourse maneuver on Sept 6 and the halo insertion on Nov 20 were monitored in near real time by observing the Sun aspect angle. Attitude and spin maneuvers were performed after each of these maneuvers to restore the attitude and spin rate to constraints.

Biases for the PAS/FSS sensors were evaluated using the Sun/Earth/Moon data from Aug. 16. (I + 4^d, after the third spin maneuver) to Sept. 4 (I + 23^d). The

PAS sensitivity has been determined to be 0.07 times the brightness of the full Moon, slightly better than the nominal value of 0.1.

A chronological summary of the major ISEE-3 events is given in Table 1-1.

1.3 SUMMARY AND CONCLUSIONS

The major conclusions referring to the attitude support activities for ISEE-3 may be summarized as follows:

- Attitude sensor performance was generally good. Very low noise levels were observed for the PAS and FSS, and only small sensor biases were encountered.
- The Moon was visible to the PAS as expected and Moon data were generally of good quality. The sensitivity of the PAS was slightly higher than expected.
- The following biases were determined for the PAS using transfer trajectory data for the Earth from $I + 4^d$ to $I + 23^d$:
  - A sensor mounting angle bias $\Delta\gamma = 0.18$ degree
  - An Earth radius bias $\Delta\rho = 0.25$ degree
  - A Moon radius bias $\Delta\rho = 0.22$ degree
  - An Earth azimuth bias $\Delta\Phi = 0.61$ degree
  - A Moon azimuth bias $\Delta\Phi = 0.64$ degree

  Other unmodeled or undetermined biases had negligible effects on attitude solutions.
- The attitude was determined and controlled well within mission requirements. As a result, the thruster firing successfully placed the spacecraft in a near nominal halo orbit and all mission events were performed in accordance with the nominal schedule.
- The attitude control system performance was near nominal.

Table 1-1. Summary of Major ISEE-3 Events

EVENT	EXECUTION TIME (YYMMDD.HHMM) GMT	POST EVENT ATTITUDE STATE						MISS	REMARKS
		DESIRED			DETERMINED				
		SPIN RATE (RPM)	α (DEG)	δ (DEG)	SPIN RATE (RPM)	α (DEG)	δ (DEG)		
LIFTOFF	780812.1512								ON TIME
INJECTION	780812.1610	46±10%	54.14	21.72	48.66	53.6	22.0	0.6 DEG, 2.66 RPM	
YO-YO DESPIN	780812.1624	9.3			10.14			0.84 RPM	
BOOM DEPLOYMENT	780812.1640	5.6			6.9			1.3 RPM	
SPIN MANEUVER 1	780812.1657	7.5			9.12			1.6 RPM	
ATTITUDE MANEUVER 1	780812.1838 (START)								
	780812.1946 (END)		277.89	61.22		281.0	64.4	3.5 DEG	ORBIT NORMAL ATTITUDE
SPIN MANEUVER 2	780812.2030	38			38.68			0.68 RPM	
ATTITUDE MANEUVER 2									CANCELLED
ORBIT MANEUVER 1	780813.1010 (START)								
	780813.1110 (END)								
ATTITUDE MANEUVER 3	780814.1010		272.48	65.45		273.08	65.30	0.3 DEG	
±V, ±U. ANTENNA	780815.1316 (START)								
DEPLOYMENT	780815.1452 (END)								
SPIN MANEUVER 3	780815.1550	19.75±0.2			19.85			0.1 RPM	MISSION SPIN RATE
ORBIT MANEUVER 2	780906.1804								
	780906.1945								
ATTITUDE MANEUVER 4	780906.2157		270.00	66.56		268.3	66.4	0.7 DEG	MISSION ATTITUDE
SPIN MANEUVER 4	780906.2240	19.75±0.2			19.77			0.02 RPM	
END OF EARLY ORBIT OPERATIONS									
ORBIT MANEUVER 3	781120.1834 (START)								HALO ORBIT INJECTION
	781120.2039 (END)								
ATTITUDE MANEUVER 5	781120.2120		270.00	66.56		269.28	66.87	0.4 DEG	
SPIN MANEUVER 5	781120.2141	19.75±0.2			19.83			0.08 RPM	
±Z AXIS DEPLOYMENT	781206.1916								
±Z AXIS DEPLOYMENT	790109.1900								
ATTITUDE MANEUVER 6	790112.1829		269.53	66.62		269.7	66.7	0.1 DEG	

- Attitude support software performed adequately throughout the mission.

1.4 DOCUMENT OVERVIEW

Section 2 of this document presents a detailed analysis of ISEE-3 attitude sensor data, including a discussion of data quality and observed anomalies. Section 3 provides the principal results of attitude and bias determination activities, including a list of implemented PAS commands, and a summary of attitude determination efforts. Section 4 gives a brief summary of the ISEE-3 control system performance.

SECTION 2 - ANALYSIS OF ATTITUDE DATA

2.1 FINE SUN SENSOR (FSS) DATA

In general, the quality of FSS data for both Sun angle and spin rate was excellent. Examples of FSS Sun Angle and Spin rate output under non-nutating conditions are shown in Table 2-1 (FSSA) and Table 2-2 (FSSB). These measurements are discussed in the following two subsections.

2.1.1 Spin Rate

The spin rate was determined onboard the spacecraft by timing successive transits of the Sun across the FSS field of view. A 16-bit register and 8192-Hz clock were used, giving a resolution of about 0.0008 rpm at 20 rpm and a minimum measurable spin rate (without register overflow) of 7.5 rpm. The spin rate was read out to 0.001 rpm in the telemetry processor and, in fact, the spin rate was observed to change in increments of 0.001 rpm, indicating noise lower than this.

2.1.2 Sun Angle

The resolution of the Sun angle measurement was approximately 0.004 degree. Examination of the tables shows occasional fluctuations of 0.001 degree over a few minutes, and systematic changes much larger than the resolution over periods of days. The former represents noise, while the latter is the true Sun angle change due to the attitude and to the motion of the Sun. Noise as high as 0.004 degree was observed occasionally.

Agreement between the Sun angles measured with the two sensors varied with Sun angle. Figure 2-1 shows the difference in the two Sun angle readings as a function of the average Sun angle. The maximum difference observed to date is about 0.12 degree, occurring at Sun angles near 39.4°. This is consistent with the maximum Sun angle difference of about 0.1° which is to be expected (the accuracy of measurement of each sensor is $\pm 0.005^{\circ}$, and the alignment on the

Table 2-1. Sun Angles From FSSA (1 of 3)

```
********************************* G E S S   V 3 ************************************
**** ISEE-C  MSAD       ***********  D I S P L A Y  ***********  78.257.21.44.10 ****
**                                                                                 **
**  RAWPF               FINAL PRIME FSS OUTPUT                      ZBDGTICS       **
**                                                                                 **
**  PRIME FSS (FSSA,FSSD)                          FSSA                            **
**  UPPER LIMIT ON SUN ANGLES                      180.0000                        **
**  LOWER LIMIT ON SUN ANGLES                        0.0                           **
**                                                                                 **
**  CRITERIA FOR ACCEPTABLE DATA:                                                  **
**   -SUN ANGLE FALLS WITHIN LIMITS                                                **
**   -QUALITY FLAG IS LESS THAN 3                                                  **
**                                                                                 **
**  WRITE ACCEPTABLE PRIME DATA                    YES                             **
**  TO FILE? (YES,NO)                                                              **
```

SAMPLE NUMBER	SAMPLE TIME YY.MM.DD.HH.MM.SS.SS	SUN ANGLE (DEGREES)	SPIN RATE (RPM)	QUALITY	FSS RECORD NUMBER
1	78.09.08.13.52.13.560	89.295	19.774	2	639
2	78.09.08.13.58.05.520	89.295	19.774	2	640
3	78.09.08.14.02.53.391	89.295	19.774	2	641
4	78.09.08.14.07.41.246	89.294	19.774	2	642
5	78.09.08.14.12.29.117	89.294	19.774	2	643
6	78.09.08.14.17.16.988	89.295	19.774	2	644
7	78.09.08.14.22.04.863	89.295	19.774	2	645
8	78.09.08.14.27.24.719	89.294	19.774	2	646
9	78.09.08.23.12.30.563	89.291	19.774	2	647
10	78.09.09.15.15.48.703	89.289	19.773	2	648
11	78.09.09.15.21.08.559	89.289	19.774	2	649
12	78.09.09.15.25.56.430	89.287	19.774	2	650
13	78.09.09.15.30.44.301	89.289	19.773	2	651
14	78.09.09.15.35.32.176	89.289	19.774	2	652
15	78.09.09.15.40.20.047	89.287	19.773	2	653
16	78.09.09.15.45.07.918	89.287	19.774	2	654
17	78.09.09.15.49.55.789	89.287	19.773	2	655
18	78.09.09.15.54.43.660	89.287	19.774	2	656
19	78.09.09.15.59.31.535	89.287	19.774	2	657
20	78.09.09.16.04.19.406	89.287	19.774	2	658
21	78.09.09.16.09.07.277	89.287	19.774	2	659
22	78.09.09.16.14.27.133	89.287	19.774	2	660
23	78.09.09.16.19.46.988	89.287	19.773	2	661
24	78.09.09.16.24.34.863	89.287	19.773	2	662
25	78.09.09.16.29.22.734	89.285	19.774	2	663

```
**  UITI READ/UNPACK CYCLE IS ENDING. UNPACK ARRAYS ARE FULL.                      **
**   CPOINT=RAWFSP WHAT NOW ? W           CALL DISPLAY        DISP   1 OF   1      **
**                                                                                 **
********************************* G E S S   V 3 ************************************
*********************************  D I S P L A Y  **********************************
```

Table 2-1. Sun Angles From FSSA (2 of 3)

```
***********************************  G E S S        V 3   ************************************
****  ISEE-C   MSAD       ***********  D I S P L A Y        ***********  78.257.21.44.25  ****
**                                                                                          **
**      RAWPR                         FINAL PRIME FSS OUTPUT                  Z6DGTICS      **
**                                                                                          **
**      PRIME FSS (FSSA,FSSD)                           FSSA                                **
**      UPPER LIMIT ON SUN ANGLES                        180.0000                           **
**      LOWER LIMIT ON SUN ANGLES                          0.0                              **
**                                                                                          **
**      CRITERIA FOR ACCEPTABLE DATA:                                                       **
**       -SUN ANGLE FALLS WITHIN LIMITS                                                     **
**       -QUALITY FLAG IS LESS THAN 3                                                       **
**                                                                                          **
**      WRITE ACCEPTABLE PRIME DATA                     YES                                 **
**      TO FILE? (YES,NO)                                                                   **
**                                                                                          **
```

SAMPLE NUMBER	SAMPLE TIME YY.MM.DD.HH.MM.SS.SS	SUN ANGLE (DEGREES)	SPIN RATE (RPM)	QUALITY	FSS RECORD NUMBER
1	78.09.09.16.34.10.590	89.287	19.774	2	689
2	78.09.09.16.38.58.461	89.285	19.773	2	690
3	78.09.09.16.43.46.336	89.285	19.774	2	691
4	78.09.09.16.48.34.207	89.287	19.773	2	692
5	78.09.09.16.53.22.078	89.285	19.774	2	693
6	78.09.09.16.58.09.949	89.287	19.774	2	694
7	78.09.09.17.02.57.820	89.287	19.774	2	695
8	78.09.09.17.07.45.695	89.287	19.773	2	696
9	78.09.10.15.11.58.094	89.281	19.773	2	697
10	78.09.10.15.16.45.965	89.281	19.773	2	698
11	78.09.10.15.22.37.805	89.281	19.773	2	699
12	78.09.10.15.27.25.680	89.281	19.774	2	700
13	78.09.10.15.32.45.535	89.281	19.774	2	701
14	78.09.10.15.37.33.406	89.281	19.774	2	702
15	78.09.10.15.42.21.277	89.281	19.774	2	703
16	78.09.10.15.47.09.148	89.281	19.773	2	704
17	78.09.10.15.51.57.023	89.281	19.773	2	705
18	78.09.10.15.57.48.863	89.281	19.774	2	706
19	78.09.10.16.03.08.719	89.281	19.773	2	707
20	78.09.10.16.08.28.574	89.281	19.773	2	708
21	78.09.10.16.13.16.445	89.281	19.773	2	709
22	78.09.10.16.19.08.285	89.281	19.773	2	710
23	78.09.10.16.23.56.156	89.281	19.773	2	711
24	78.09.10.16.45.15.562	89.281	19.773	2	712
25	78.09.10.16.50.03.453	89.281	19.774	2	713

```
**                                                                                          **
**   UIII READ/UNPACK CYCLE IS ENDING. UNPACK ARRAYS ARE FULL.                              **
**     CPOINT=RAWFSP WHAT NOW ? W              CALL DISPLAY            DISP   1 OF   1      **
**                                                                                          **
***********************************  G E S S        V 3   ************************************
***********************************  D I S P L A Y        ************************************
```

Table 2-1. Sun Angles From FSSA (3 of 3)

```
************************************  G E S S    V 3   ****************************************
****  ISEE-C  MSAD        ***********   D I S P L A Y    ***********  78.257.21.45.25  ****
**                                                                                        **
**      RAWPR                        FINAL PRIME FSS OUTPUT                   ZBDGTICS    **
**                                                                                        **
**      PRIME FSS (FSSA,FSSD)                             FSSA                            **
**      UPPER LIMIT ON SUN ANGLES                         180.0000                        **
**      LOWER LIMIT ON SUN ANGLES                         0.0                             **
**                                                                                        **
**      CRITERIA FOR ACCEPTABLE DATA:                                                     **
**       -SUN ANGLE FALLS WITHIN LIMITS                                                   **
**       -QUALITY FLAG IS LESS THAN 3                                                     **
**                                                                                        **
**      WRITE ACCEPTABLE PRIME DATA                       YES                             **
**      TO FILE? (YES,NO)                                                                 **
**                                                                                        **
**     SAMPLE        SAMPLE TIME          SUN ANGLE SPIN RATE QUALITY FSS RECORD          **
**     NUMBER   YY.MM.DD.HH.MM.SS.SS     (DEGREES)    (RPM)              NUMBER           **
**          1   78.09.10.16.54.51.324      89.281     19.773     2         739            **
**          2   78.09.10.16.59.39.199      89.281     19.774     2         740            **
**          3   78.09.08.14.15.41.039      89.294     19.774     3         741            **
**          4   78.09.08.14.20.28.910      89.294     19.774     3         742            **
**          5   78.09.08.14.25.16.781      89.295     19.774     3         743            **
**          6   78.09.08.14.30.04.652      89.294     19.773     3         744            **
**          7   78.09.08.14.35.56.492      89.295     19.774     3         745            **
**          8   78.09.08.14.40.44.367      89.294     19.774     3         746            **
**          9   78.09.08.14.45.32.238      89.294     19.774     3         747            **
**         10   78.09.08.14.50.52.094      89.294     19.774     3         748            **
**         11   78.09.08.14.55.39.965      89.294     19.774     3         749            **
**         12   78.09.08.15.00.27.840      89.294     19.774     3         750            **
**         13   78.09.08.15.06.51.660      89.294     19.774     3         751            **
**         14   78.09.08.15.11.39.535      89.294     19.774     3         752            **
**         15   78.09.08.15.16.27.456      89.294     19.774     3         753            **
**         16   78.09.08.14.54.35.980      89.294     19.774     3         754            **
**         17   78.09.08.14.59.23.855      89.294     19.774     3         755            **
**         18   78.09.08.15.05.47.695      89.295     19.774     3         756            **
**         19   78.09.08.15.10.35.566      89.294     19.774     3         757            **
**         20   78.09.08.15.15.23.422      89.294     19.774     3         758            **
**         21   78.09.08.15.21.15.277      89.295     19.774     3         759            **
**         22   78.09.08.15.26.03.133      89.294     19.774     3         760            **
**         23   78.09.08.15.30.51.008      89.294     19.774     3         761            **
**         24   78.09.08.15.36.10.863      89.294     19.774     3         762            **
**         25   78.09.08.15.40.58.734      89.294     19.774     3         763            **
**                                                                                        **
**                                                                                        **
**    UIII READ/UNPACK CYCLE IS ENDING. UNPACK ARRAYS ARE FULL.                           **
**      CPCINT=RAWFSP WHAT NOW ? W             CALL DISPLAY            DISP   1 OF   1    **
**                                                                                        **
************************************   G E S S     V 3   **************************************
************************************   D I S P L A Y     **************************************
```

Table 2-2. Sun Angles From FSSB (1 of 3)

```
ISEE-C  MSAD          G E S S  D I S P L A Y  V 3          78.257.21.44.19

RAWDA                          FINAL BACKUP FSS OUTPUT              ZBDGTICS
BACKUP FSS (FSSA,FSSB)                  FSSB
UPPER LIMIT CN SUN ANGLES               180.0000
LOWER LIMIT CN SUN ANGLES                 0.0

CRITERIA FOR ACCEPTABLE DATA:
  -SUN ANGLE FALLS WITHIN LIMITS
  -QUALITY FLAG IS LESS THAN 3

WRITE ACCEPTABLE BACKUP DATA            YES
TO FILE? (YES,NC)
```

SAMPLE NUMBER	SAMPLE TIME YY.MM.DD.HH.MM.SS.SS	SUN ANGLE (DEGREES)	SPIN RATE (RPM)	QUALITY	FSS RECORD NUMBER
1	78.09.08.13.52.13.660	89.447	19.774	2	664
2	78.09.08.13.58.05.520	89.447	19.774	2	665
3	78.09.08.14.02.53.391	89.447	19.774	2	666
4	78.09.08.14.07.41.246	89.444	19.774	2	667
5	78.09.08.14.12.29.117	89.444	19.774	2	668
6	78.09.08.14.17.16.988	89.447	19.774	2	669
7	78.09.08.14.22.04.863	89.447	19.774	2	670
8	78.09.08.14.27.24.719	89.447	19.774	2	671
9	78.09.08.23.12.30.563	89.444	19.774	2	672
10	78.09.09.15.15.48.703	89.438	19.773	2	673
11	78.09.09.15.21.08.559	89.438	19.774	2	674
12	78.09.09.15.25.56.430	89.438	19.774	2	675
13	78.09.09.15.30.44.301	89.438	19.773	2	676
14	78.09.09.15.35.32.176	89.438	19.774	2	677
15	78.09.09.15.40.20.047	89.438	19.773	2	678
16	78.09.09.15.45.07.918	89.438	19.774	2	679
17	78.09.09.15.49.55.789	89.438	19.773	2	680
18	78.09.09.15.54.43.660	89.438	19.774	2	681
19	78.09.09.15.59.31.535	89.438	19.774	2	682
20	78.09.09.16.04.19.406	89.438	19.774	2	683
21	78.09.09.16.09.07.277	89.438	19.774	2	684
22	78.09.09.16.14.27.133	89.438	19.774	2	685
23	78.09.09.16.19.46.998	89.438	19.773	2	686
24	78.09.09.16.24.34.863	89.438	19.773	2	687
25	78.09.09.16.29.22.734	89.438	19.774	2	688

```
CPCINT=PAWFSB WHAT NOW ? W          CALL DISPLAY          DISP   1 OF   1
                              G E S S  D I S P L A Y  V 3
```

Table 2-2. Sun Angles From FSSB (2 of 3)

```
******************************  G E S S    V 3  ************************************
****  ISEE-C  MSAO    ***********  D I S P L A Y  ***********  78.257.21.44.33  ****

      RAWBA                    FINAL BACKUP FSS OUTPUT                 ZBDGTICS
      BACKUP FSS (FSSA,FSSB)                 FSSB
      UPPER LIMIT ON SUN ANGLES             180.0000
      LOWER LIMIT ON SUN ANGLES               0.0

      CRITERIA FOR ACCEPTABLE DATA:
       -SUN ANGLE FALLS WITHIN LIMITS
       -QUALITY FLAG IS LESS THAN 3

      WRITE ACCEPTABLE BACKUP DATA           YES
      TO FILE? (YES,NO)
```

SAMPLE NUMBER	SAMPLE TIME YY.MM.DD.HH.MM.SS.SS	SUN ANGLE (DEGREES)	SPIN RATE (RPM)	QUALITY	FSS RECORD NUMBER
1	78.09.09.16.34.10.590	89.438	19.774	2	714
2	78.09.09.16.38.58.461	89.438	19.773	2	715
3	78.09.09.16.43.46.336	89.438	19.774	2	716
4	78.09.09.16.48.34.207	89.438	19.773	2	717
5	78.09.09.16.53.22.078	89.438	19.774	2	718
6	78.09.09.16.58.09.949	89.438	19.774	2	719
7	78.09.09.17.02.57.820	89.438	19.774	2	720
8	78.09.09.17.07.45.695	89.438	19.773	2	721
9	78.09.10.15.11.58.094	89.433	19.773	2	722
10	78.09.10.15.16.45.965	89.433	19.773	2	723
11	78.09.10.15.22.37.805	89.433	19.773	2	724
12	78.09.10.15.27.25.680	89.433	19.774	2	725
13	78.09.10.15.32.45.535	89.433	19.774	2	726
14	78.09.10.15.37.33.466	89.433	19.774	2	727
15	78.09.10.15.42.21.277	89.433	19.774	2	728
16	78.09.10.15.47.09.148	89.433	19.773	2	729
17	78.09.10.15.51.57.023	89.433	19.773	2	730
18	78.09.10.15.57.48.863	89.433	19.774	2	731
19	78.09.10.16.03.58.719	89.433	19.773	2	732
20	78.09.10.16.08.28.574	89.433	19.773	2	733
21	78.09.10.16.13.16.445	89.433	19.773	2	734
22	78.09.10.16.19.08.265	89.433	19.773	2	735
23	78.09.10.16.23.56.156	89.433	19.773	2	736
24	78.09.10.16.45.15.582	89.433	19.773	2	737
25	78.09.10.16.50.03.453	89.433	19.774	2	738

```
      CPOINT=RAWFSB WHAT NOW ? W          CALL DISPLAY          DISP   1 OF   1
******************************  G E S S    V 3  ************************************
******************************  D I S P L A Y  ************************************
```

Table 2-2. Sun Angles From FSSB (3 of 3)

GESS V3 DISPLAY

ISEE-C MSAD 78.257.21.45.36

RAWBA FINAL BACKUP FSS OUTPUT ZBDGTICS

BACKUP FSS (FSSA,FSSB) FSSB

UPPER LIMIT ON SUN ANGLES 180.0000

LOWER LIMIT ON SUN ANGLES 0.0

CRITERIA FOR ACCEPTABLE DATA:

-SUN ANGLE FALLS WITHIN LIMITS

-QUALITY FLAG IS LESS THAN 3

WRITE ACCEPTABLE BACKUP DATA TO FILE? (YES,NO) YES

SAMPLE NUMBER	SAMPLE TIME YY.MM.DD.HH.MM.SS.SS	SUN ANGLE (DEGREES)	SPIN RATE (RPM)	QUALITY	FSS RECORD NUMBER
1	78.09.10.16.54.51.324	89.433	19.773	2	741
2	78.09.10.16.59.39.199	89.433	19.774	2	742
3	78.09.08.14.15.41.039	89.444	19.774	3	743
4	78.09.08.14.20.28.910	89.444	19.774	3	744
5	78.09.08.14.25.16.781	89.447	19.774	3	745
6	78.09.08.14.30.04.652	89.447	19.773	3	746
7	78.09.08.14.35.56.492	89.447	19.774	3	747
8	78.09.08.14.40.44.367	89.447	19.774	3	748
9	78.09.08.14.45.32.238	89.444	19.774	3	749
10	78.09.08.14.50.52.094	89.444	19.774	3	750
11	78.09.08.14.55.39.965	89.444	19.774	3	751
12	78.09.08.15.00.27.840	89.447	19.774	3	752
13	78.09.08.15.06.51.660	89.444	19.774	3	753
14	78.09.08.15.11.39.535	89.444	19.774	3	754
15	78.09.08.15.16.27.406	89.447	19.774	3	755
16	78.09.08.14.54.35.980	89.447	19.774	3	756
17	78.09.08.14.59.23.855	89.444	19.774	3	757
18	78.09.08.15.05.47.695	89.447	19.774	3	758
19	78.09.08.15.10.35.566	89.447	19.774	3	759
20	78.09.08.15.15.23.422	89.444	19.774	3	760
21	78.09.08.15.21.15.277	89.447	19.774	3	761
22	78.09.08.15.26.03.133	89.444	19.774	3	762
23	78.09.08.15.30.51.008	89.444	19.774	3	763
24	78.09.08.15.36.10.863	89.444	19.774	3	764
25	78.09.08.15.40.58.734	89.444	19.774	3	765

CPCINT=RAWFSB WHAT NOW ? W CALL DISPLAY DISP 1 OF 1

GESS V3 DISPLAY

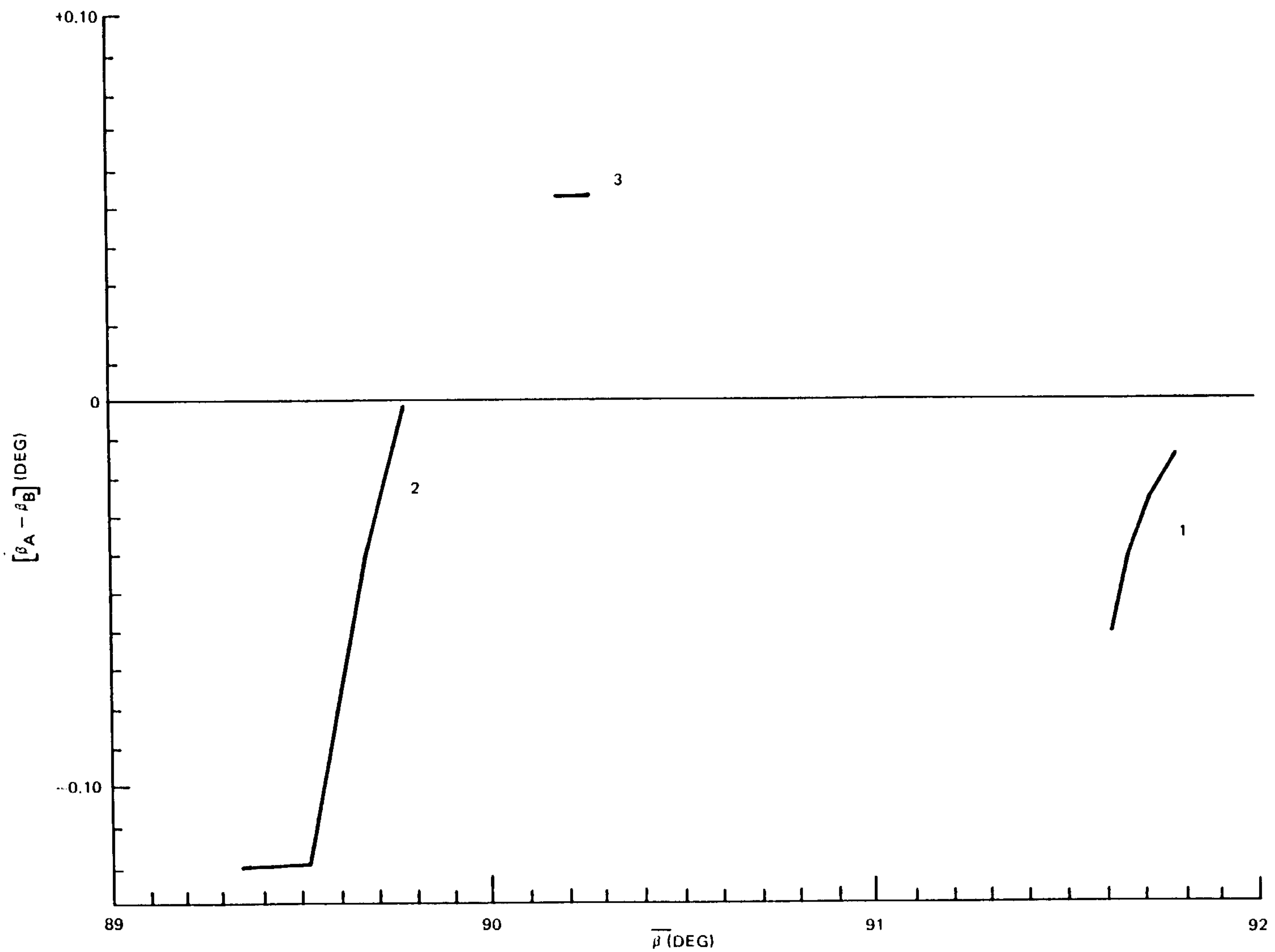

Figure 2-1. Comparison of Sun Angle Measurements Between FSSA and FSSB

spacecraft is within 0.05 degree, so that the root sum square is 0.07 degree for each sensor, or 0.1 degree between them).

On several passes grossly incorrect values of Sun angle, spin rate, and/or time were observed. These were infrequent, easily identified, and did not cause any significant problem.

2.2 PAS/FSS DATA

In general, the quality of the attitude data obtained from the PAS was excellent.

2.2.1 Spin Rate

The spin rate was normally computed from the FSS data (Section 2.1), but it can be computed with the data in a PAS register not containing horizon-crossing data. The only time the latter method was attempted was during the period following the boom deployments when the spin rate dropped below 7.5 rpm. During this period, however, the PAS telescope was pointing at the spacecraft and no valid data were obtained.

2.2.2 Earth Data

The quality of Earth PAS data throughout the mission was excellent. Low noise levels were observed, little or no Sun interference was encountered even for small Sun-Earth separations, and Earth sightings were obtained throughout the mission.

Figures 2-2 through 2-6 give typical results for Earth PAS data. Figure 2-2 is a plot of the PAS encoder angle versus time over an 8-hour period, starting at 1642 GMT, Aug. 16, 1978. Figure 2-3 shows the measured Earth-in and Earth-out rotation angles for the same period. The values centered on 360 degrees (not shown in the figure) represent Sun sightings. From the indicated in- and out-crossings, the apparent width of the Sun is approximately 24 degrees, which agrees with prelaunch evaluations of PAS performance. Figure 2-4 represents the Earth scan widths for these data. Figure 2-5 shows predicted

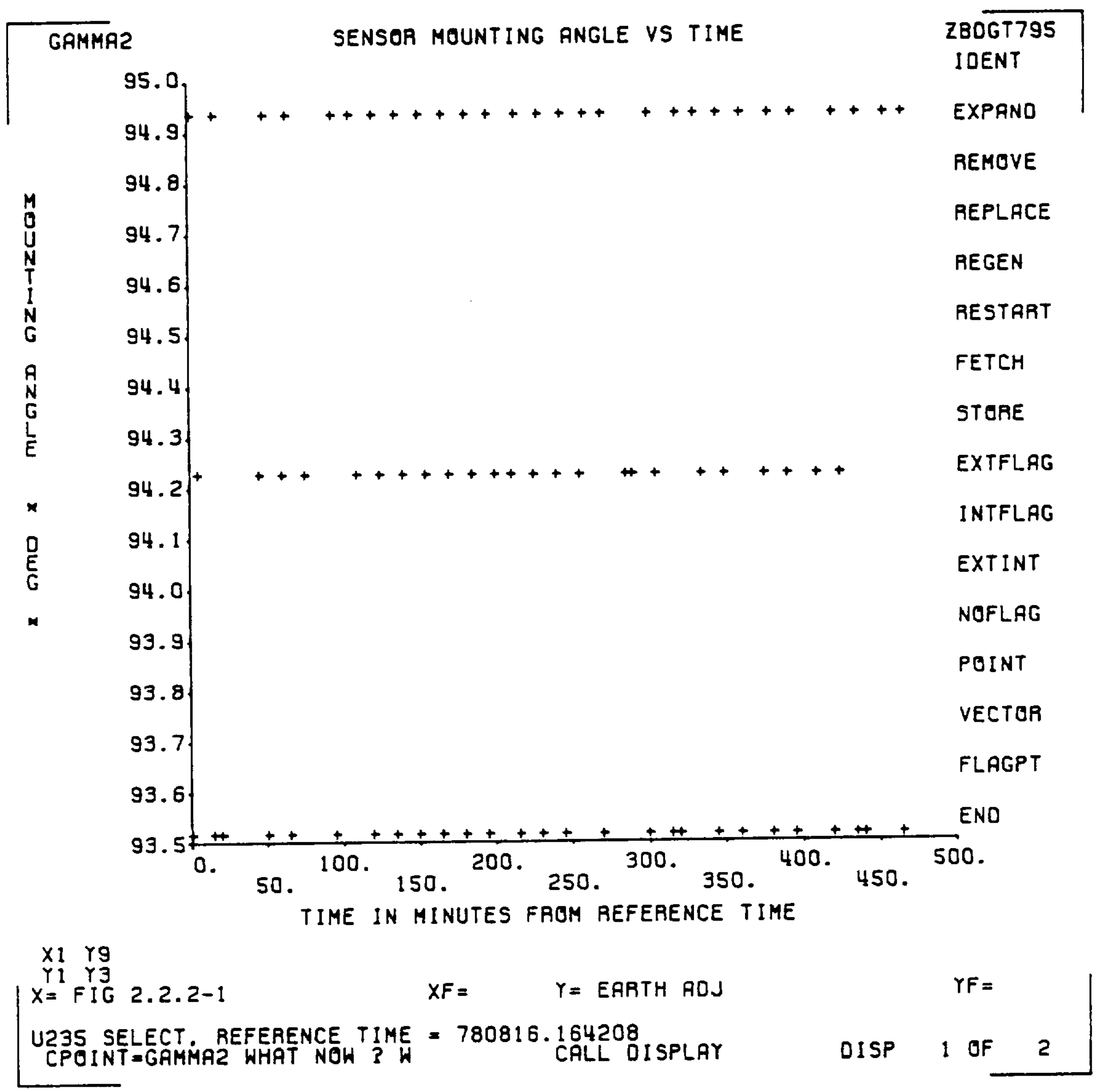

Figure 2-2. PAS Encoder Angle vs Time

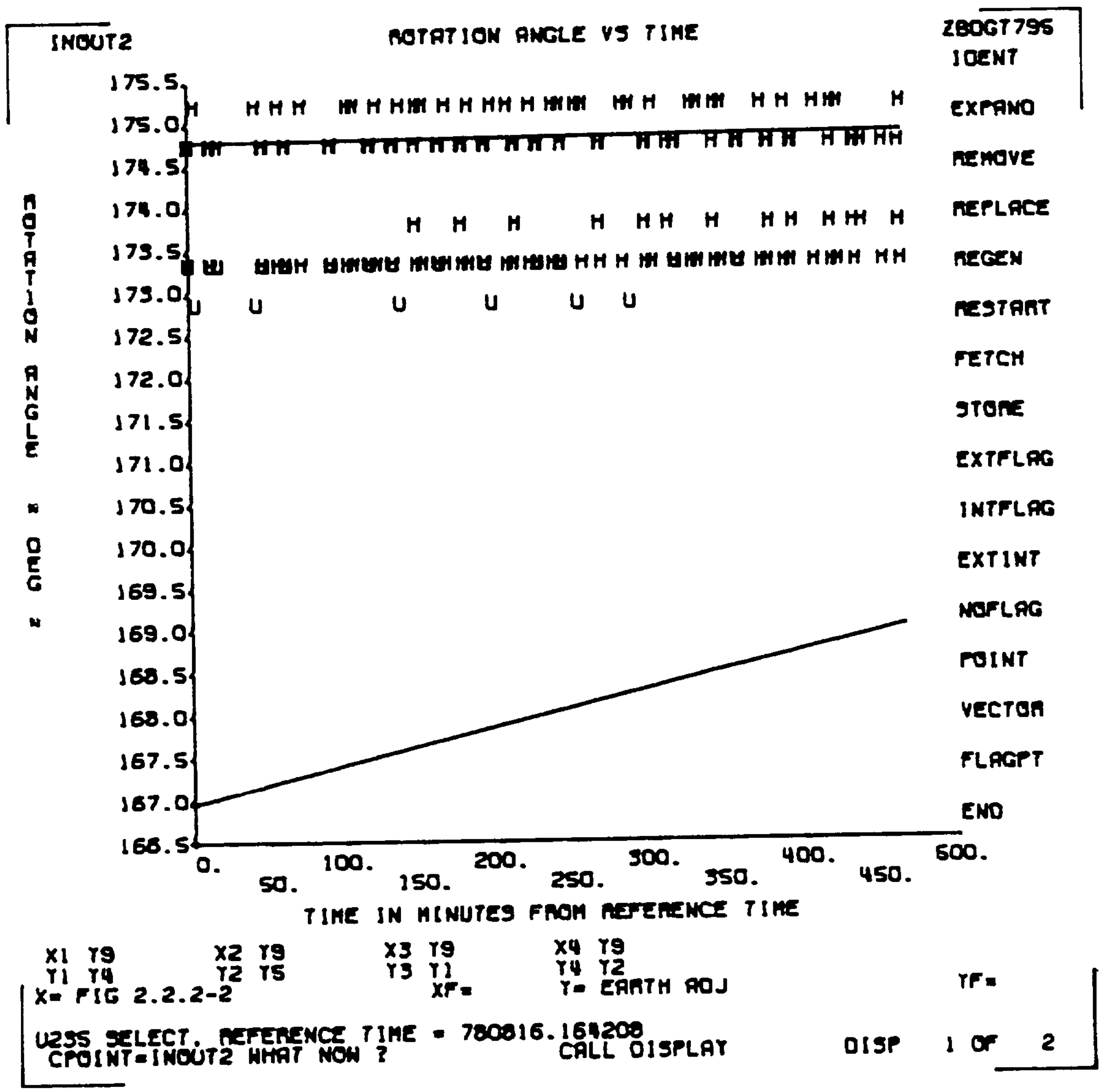

Figure 2-3. Earth-In and Earth-Out Rotation Angles vs Time

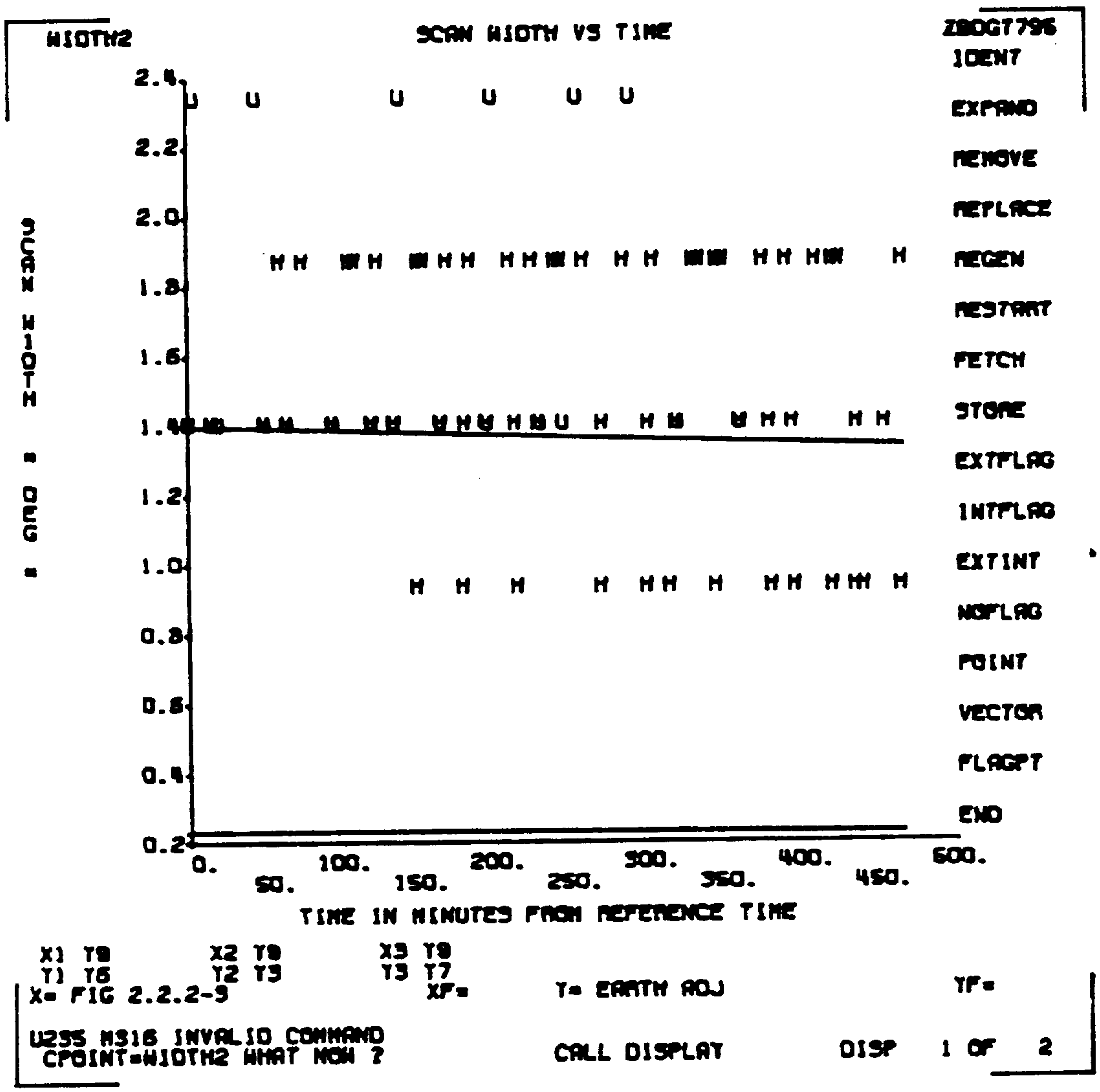

Figure 2-4. Earth Scan Width vs Time

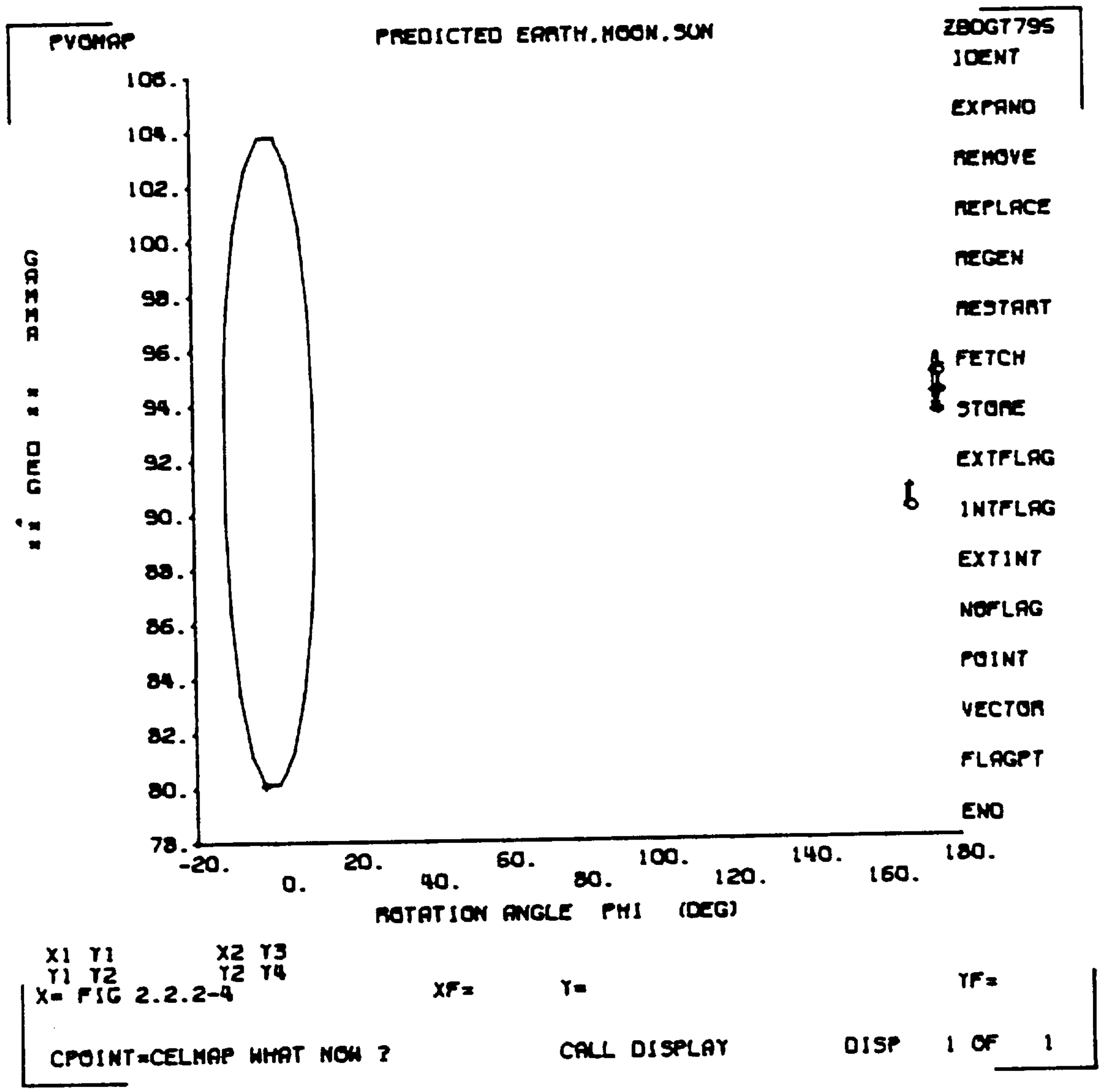

Figure 2-5. Celestial Sphere Plot Showing Sun, Moon, and Earth Events

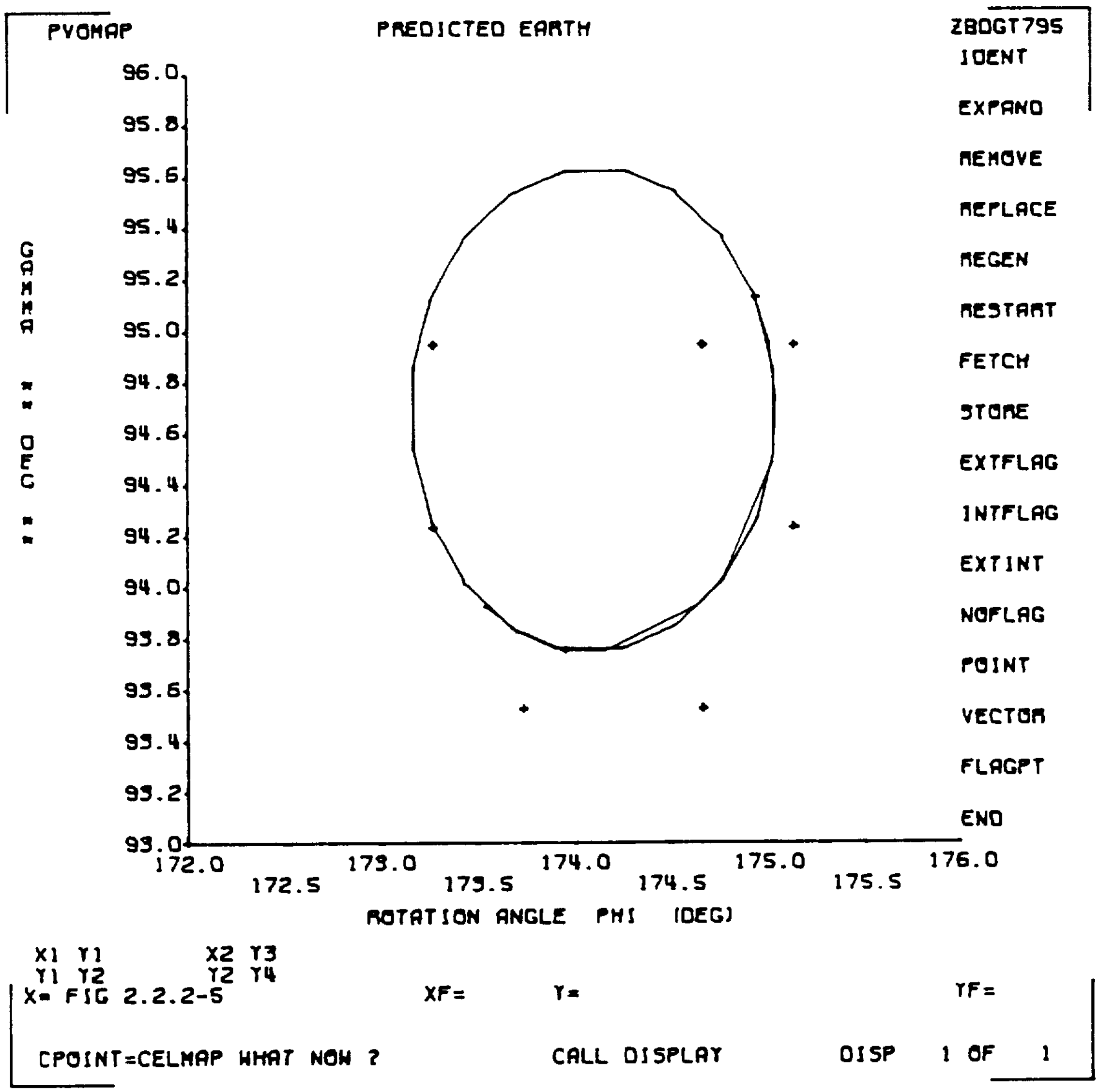

Figure 2-6. Detail of Celestial Sphere Plot Showing Earth Horizon Triggerings

Earth, Moon, and Sun positions, and Earth and Moon in- and out-crossing events. Figure 2-6 is an enlargement of the predicted-versus-observed Earth events for this interval.

2.2.3 Moon Data

The quality of the Moon PAS data throughout the mission was excellent. Moon sightings were obtained whenever the Moon's integrated visual magnitude was less than -10.0; the PAS trigger level is thus 0.07 times the maximum radiance of the full Moon, slightly less than the specified level of 0.10.

Figures 2-7 and 2-8 give typical results for Moon PAS data. Figure 2-7 shows the measured Moon in- and out-rotation angles for a 9-hour period starting at 1639 GMT, Aug. 16, 1978.

Figure 2-8 is an enlargement of the predicted-versus-observed Moon events for this interval.

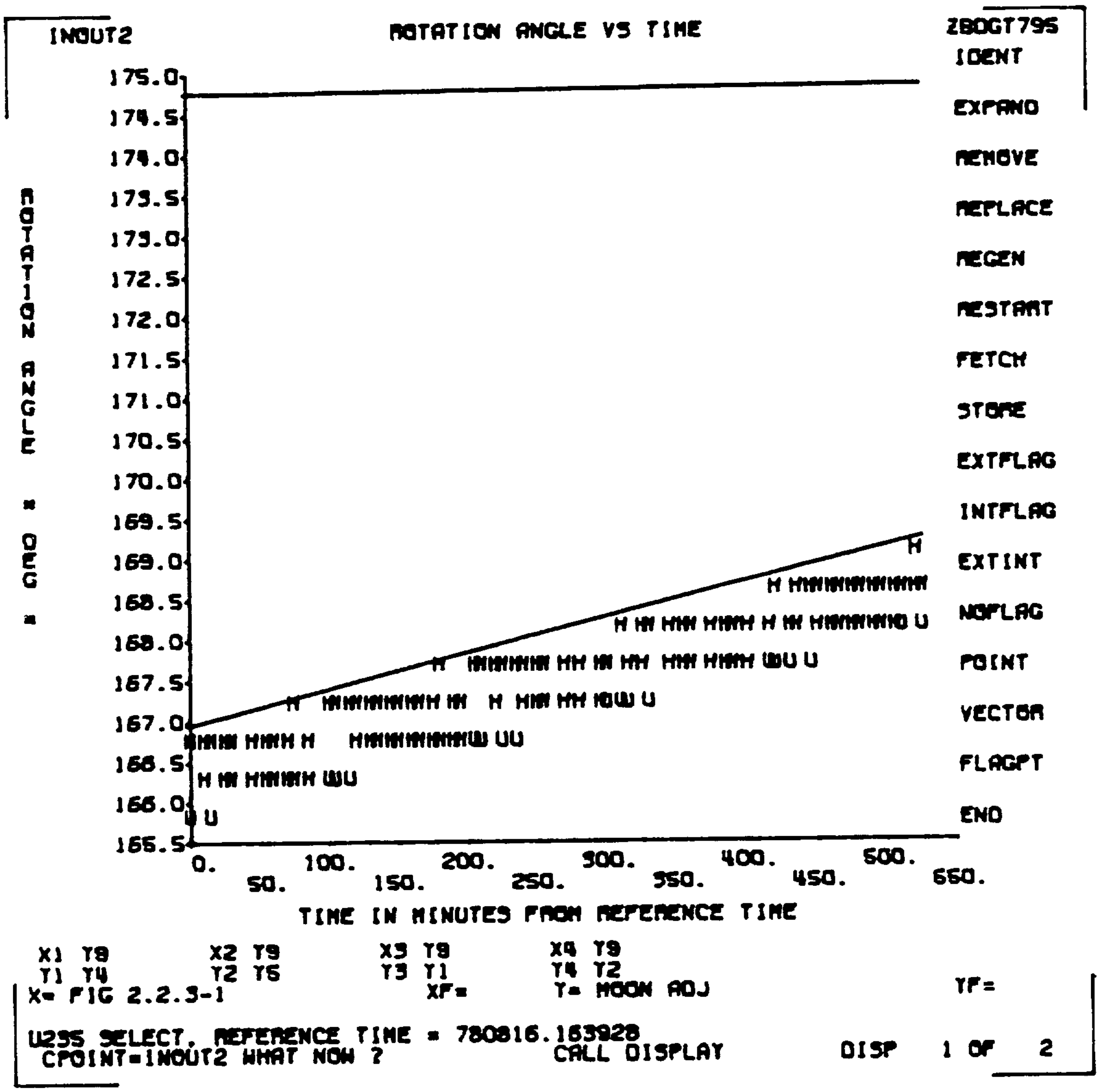

Figure 2-7. Moon-In and Moon-Out Rotation Angles vs Time

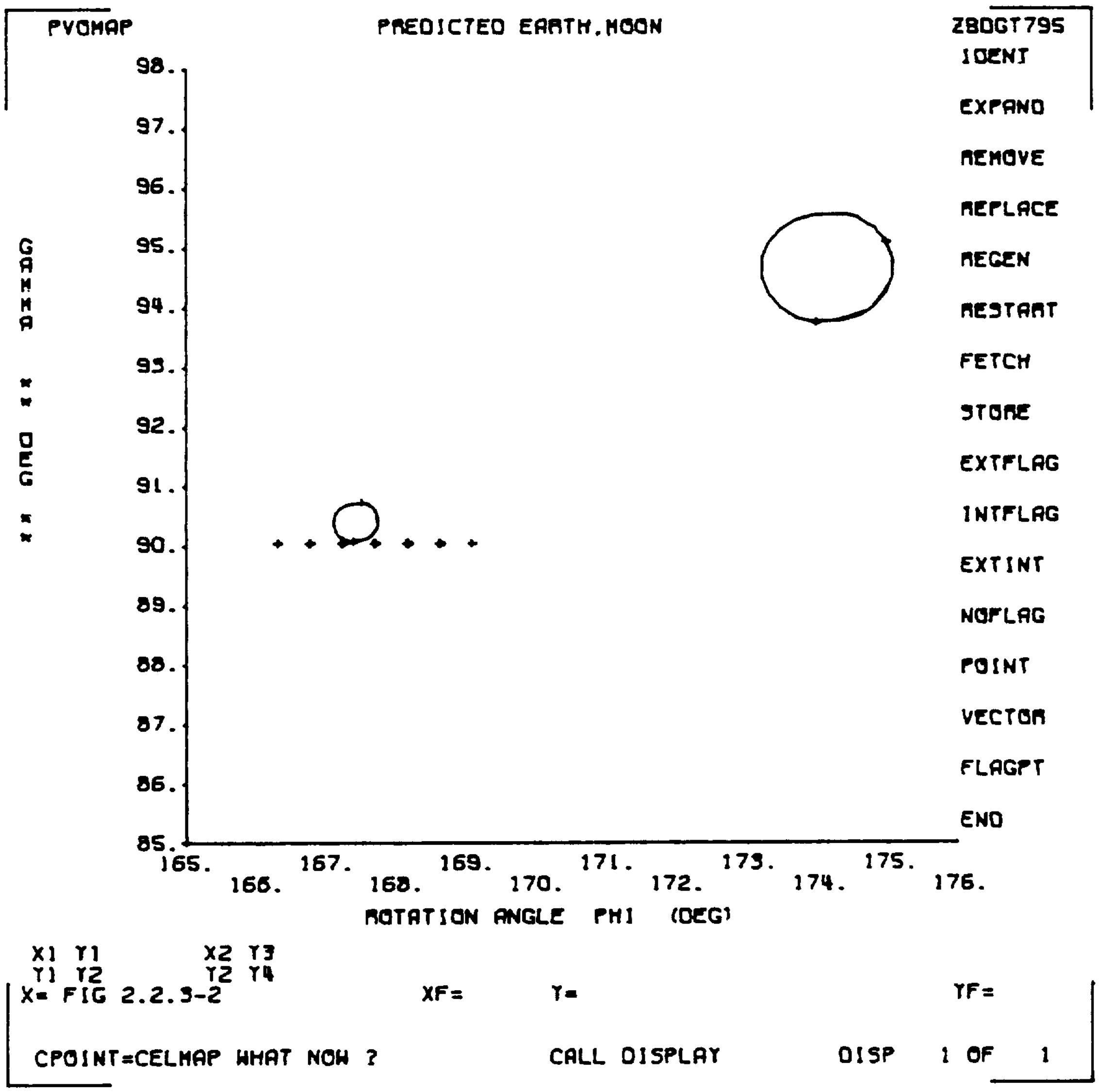

Figure 2-8. Detail of Celestial Sphere Plot (Figure 2-5) Showing Moon Horizon Triggerings

SECTION 3 - ATTITUDE AND BIAS DETERMINATION RESULTS

3.1 ATTITUDE AND BIAS DETERMINATION RESULTS FOR THE PAS/FSS MODE

This section summarizes the attitude and bias results obtained for ISEE-3 from injection through the fourth attitude maneuver (Sept. 6, 1978). Included are the following: discussions of the PAS command strategy, the implemented PAS commands, and a summary of the principal attitude and bias solutions which were obtained.

3.1.1 PAS Command Strategy and Implemented PAS Commands

Throughout the mission, the PAS command strategy was designed to maximize data coverage. The encoder angle ranges for which the Earth and the Moon would be visible were determined using the PAS data predictor (PASDP) and the analysis program (OSAG). The PAS generally was commanded to execute a sector scan over the range of angles that included both the Earth and the Moon, even when the Moon was expected to be too dim to trigger the PAS.

A summary of the implemented PAS commands for the early mission trajectory is listed in Table 3-1.

3.1.2 Software Performance

Software performance was excellent for the attitude determination and control support provided for the ISEE-3 mission. No significant problems were encountered in the operation of the system.

3.1.3 Bias Determination Results

The principal PASS/FSS mode bias determination results for the Earth and Moon obtained for ISEE-3 are summarized in Table 3-2. The sensor biases (systematic errors) were determined with the least-squares OABIAS subsystem in MSAD/ISEE-C. The time period between I + 4 days (Aug. 16, 1978) and

Table 3-1. Implemented PAS Commands for the Early Mission Trajectory

DATE (YYMMDD.HHMM)	PAS COMMAND			
	θMAX (DEG)	θMIN (DEG)	CLOCK FREQUENCY (HZ)	DIRECTION
780812.1750	150	120	128	CW
780812.2100	100	78	512	CW
780812.2200	88	84	512	CW
780813.0345	88	84	1024	CW
780813.0900	88	84	512	CW
780813.1145	41	86	512	CW
780814.0902	89.3	88.6	512	CW
780814.1300	90.7	88.6	512	CW
780815.1800	92.0	84.0	256	CW
780815.1900	82	92	256	CW
780816.1300	97	87	256	CW
781101.1800	70	90	1024	CCW
790112.1800	80	98	1024	CW

Table 3-2. Summary of the PAS/FSS Bias Determination Results

TARGET	CASE NO.	ATTITUDE		BIASES (DEGREES)									
		α (DEG)	δ (DEG)	$\Delta\beta$	ϵ_β	$\Delta\gamma$	$\Delta\varphi$ IN = $\Delta\varphi$ OUT	$\Delta\varphi$ IN	$\Delta\varphi$ OUT	$\Delta\rho$ IN = $\Delta\rho$ OUT	$\Delta\rho$ IN	$\Delta\rho$ OUT	ϵ_ρ
(a) EARTH ONLY	1	272.95	65.31	[0.002]	[−0.095]	0.18	YES	0.61	0.61	YES	0.25	0.25	[−0.094]
	2	272.95	65.31	[0.002]	−0.098	[0.18]	–	[0.61]	[0.61]	–	[0.25]	[0.25]	[−0.094]
	3	272.95	65.31	[0.002]	[−0.098]	[0.18]	–	[0.61]	[0.61]	–	[0.25]	[0.25]	−0.091
	4	272.95	65.31	0.002	[−0.098]	[0.18]	–	[0.61]	[0.61]	–	[0.25]	[0.25]	[−0.091]
PREFERRED →	5	272.95	65.31	[0.002]	[−0.098]	0.18	YES	0.61	0.61	YES	0.25	0.25	[−0.091]
	6	272.95	65.31	[0.002]	[−0.098]	0.18	NO	0.63	0.60	YES	0.24	0.24	[−0.091]
	7	272.95	65.31	[0.002]	[−0.098]	0.18	NO	0.63	0.60	NO	0.25	0.25	[−0.091]
	8	272.95	65.31	[0.002]	[−0.098]	[0.18]	–	[0.63]	[0.60]	–	[0.24]	[0.24]	−0.084
	9	272.95	65.31	[0.002]	−0.092	[0.18]	–	[0.63]	[0.60]	–	[0.24]	[0.24]	[−0.084]
(b) MOON ONLY	10	272.95	65.31	[0.002]	[−0.098]	[0.18]	YES	0.64	0.64	YES	0.22	0.22	[−0.091]
	11	272.95	65.31	[0.002]	[−0.098]	0.18	YES	0.64	0.64	YES	0.22	0.22	[−0.091]
	12	272.95	65.31	[0.002]	−0.11	[0.18]	–	[0.64]	[0.64]	–	[0.22]	[0.22]	[−0.091]
	13	272.95	65.31	[0.002]	[−0.11]	[0.18]	–	[0.64]	[0.64]	–	[0.22]	[0.22]	−0.07
	14	272.95	65.31	0.002	[−0.11]	[0.18]	–	[0.64]	[0.64]	–	[0.22]	[0.22]	[−0.07]
PREFERRED →	15	272.95	65.31	[0.002]	[−0.11]	0.18	YES	0.64	0.64	YES	0.22	0.22	[−0.07]
	16	272.95	65.31	[0.002]	[0.11]	0.17	NO	0.60	0.71	YES	0.25	0.25	[−0.07]
	17	272.93	65.29	[0.002]	[−0.11]	[0.17]	–	[0.60]	[0.71]	NO	0.25	0.17	[−0.07]

NOTE: NUMBERS IN SQUARE BRACKETS WERE FIXED AT THESE VALUES AND NOT SOLVED-FOR PARAMETERS
α AND δ ARE THE RIGHT ASCENSION AND DECLINATION OF THE ATTITUDE VECTOR.
Δ_β IS THE SUN ANGLE BIAS.
ϵ_β IS THE SUN SENSOR PLANE TILT.
Δ_γ IS THE MOUNTING ANGLE BIAS.
$\Delta\varphi_{IN}$ AND $\Delta\varphi_{OUT}$ ARE THE IN- AND OUT-AZIMUTH BIASES.
$\Delta\rho_{IN}$ AND $\Delta\rho_{OUT}$ ARE THE IN- AND OUT-RHO BIASES
$\Delta\varphi_{IN} = \Delta\varphi_{OUT}$ IS THE CONSTRAINT FIXING THE AZIMUTH BIASES TO BE EQUAL DURING THE FITTING.
$\Delta\rho_{IN} = \Delta\rho_{OUT}$ IS THE CONSTRAINT FIXING THE RHO BIASES TO BE EQUAL DURING THE FITTING.

I + 23 days (Sept. 4, 1978) was chosen since it was the longest period close to Earth with no maneuvers of any kind. A time period between maneuvers was chosen to ensure that the attitude would be constant. The farther the spacecraft travels from the Earth and the Moon, the less time variation there is in the Earth nadir angle, the Sun-to-Earth rotation angle, the Moon nadir angle, and the Sun-to-Moon rotation angle; that is, the later in the mission, the smaller the time variation in the "geometry." However, the least-squares fitting procedure requires as large a variation in the geometry as possible to accurately solve for the biases. Therefore, a timespan was chosen which was close to Earth and of sufficient duration to obtain the greatest possible geometry variation.

Included in the table are the determined right ascension (α) and declination (δ) of the spin-axis attitude, as well as the estimated sensor biases for PAS1 and FSSA obtained for the time interval. $\Delta\beta$ is the Sun angle bias; $\Delta\gamma$ is the mounting angle bias; ϵ_β is the Sun sensor plane tilt; ϵ_ρ is the PAS plane tilt; $\Delta\Phi_{in}$ and $\Delta\Phi_{out}$ are correspondingly the in- and out-azimuth biases; and $\Delta\rho_{in}$ and $\Delta\rho_{out}$ are correspondingly the in- and out-rho biases (biases on the radius of the central body). Also included in the table are the azimuth constraint option fixing $\Delta\Phi_{in}$ equal to $\Delta\Phi_{out}$, and the rho constraint option fixing $\Delta\rho_{in}$ equal to $\Delta\rho_{out}$.

Values for the sensor biases included within square brackets were fixed quantities and were not solved for.

The Attitude and Bias Observability System (ABOS, Reference 6) was used to develop a bias determination plan, and the top-to-bottom arrangement of Table 3-2 gives the order in which the fittings were carried out.

The ephemeris used to evaluate the attitude and bias solutions was the definitive estimate.

Throughout this period, the estimated uncertainty in the determined attitude, was approximately 2 degrees.

The difference between $\Delta\Phi_{in}$ and $\Delta\Phi_{out}$ and $\Delta\rho_{in}$ and $\Delta\rho_{out}$ was too small to be significant, so the solutions in which they were equal were preferred to the solutions where $\Delta\Phi_{in} \neq \Delta\Phi_{out}$ or $\Delta\rho_{in} \neq \Delta\rho_{out}$.

The final estimates for the magnitudes of the sensor biases (in degrees) are for the Earth (case 5 in Table 3-2): $\Delta\Phi = 0.06$, $\Delta\rho = \Delta\rho_{in} = \Delta\rho_{out} = 0.25$, $\Delta\gamma = 0.18$, $\Delta\beta = 0.002$, $\epsilon_{\beta} = -0.098$, and $\epsilon_{\rho} = 0.091$; for the Moon (case 15 in Table 3-2): $\Delta\Phi = \Delta\Phi_{in} = \Delta\Phi_{out} = 0.064$, $\Delta\rho = 0.22$, $\Delta\gamma = 0.18$, $\Delta\beta = 0.002$, $\epsilon_{\beta} = 0.11$, and $\epsilon_{\rho} = 0.069$. The biases for the Earth and Moon solutions agree very well, but the $\Delta\rho$ for the Earth is larger because the Earth is brighter than the Moon.

Figures 3-1 through 3-5 show the results for attitude and bias solutions, for the Earth, from $I + 4^d$ to $I + 23^d$. Figure 3-1 gives the encoder angles at which Earth-in- and Earth-out-crossings occurred over this period. The Sun angles corresponding to the selected data are plotted in Figure 3-2, and the spin rate data in Figure 3-3. Figures 3-4 and 3-5 give the in- and out-crossing rotation angles (the rotation angles about the attitude from the Sun to the Earth horizons) and Earth widths for the selected data. Points are identified as horizon crossings (H), terminator crossings (T), or are unidentified (U).

Figures 3-6 through 3-9 show plots of the residuals (the fit minus the measurement) obtained from OABIAS versus frame number for case 5 in Table 3-2. The residuals from the Sun angle, horizon-in-crossing, horizon-out-crossing, and mounting angle (point source model) of measurements are plotted.

Figures 3-10 through 3-12 show the predicted versus observed results using the Earth OABIAS solution of case 5 in Table 3-2. Figure 3-10 gives the celestial sphere plot showing Moon and Earth data. In this figure, gamma (the PAS mountin angle) is plotted versus phi (the rotation angle about the attitude from the Sun to the Earth horizons). The large oval represents the location of the Earth and the small rectangle the location of the Moon, as predicted using the attitude and the biases from case 5 in Table 3-2. The measured gammas and phis for Earth and Moon data are plotted as crosses. Figure 3-11 gives the predicted and observed Sun-to-Earth rotation angles, and Figure 3-12 shows the predicted and observed scan widths for PAS1.

Results for the deterministic attitude solutions obtained from the Earth data between $I + 4^d$ and $I + 23^d$ are $\alpha = 272.8$ degrees and $\delta = 65.0$ degrees as shown in Figures 3-13 and 3-15. The sensor biases for case 5 in Table 3-2 were applied to the data to obtain the solution. The uncertainty associated with the derived attitude solution was 1.8 degree. This result is in good agreement with the OABIAS solution. Figure 3-13 shows the computed right ascension of the attitude versus time for five attitude determination methods after ambiguity resolution. (Each attitude determination method may yield as many as four different solutions for the attitude vector; the correct attitude is determined by comparison to the a priori attitude and by block-average methods.) Figure 3-14 gives the corresponding results for the declination. The plots of the α and δ solutions for any one method are fairly constant in time, indicating that there are no significant unsolved biases. The different attitude determination methods (discussed in Reference 1) yield solutions for α and δ that agree within $\pm$ 1 degree; thus, the specified attitude uncertainty of $\pm$ 1 degree has been met. The measured attitude uncertainty would have been improved with higher PAS clock frequencies.

A plot of computed right ascension versus declination is shown in Figure 3-15.

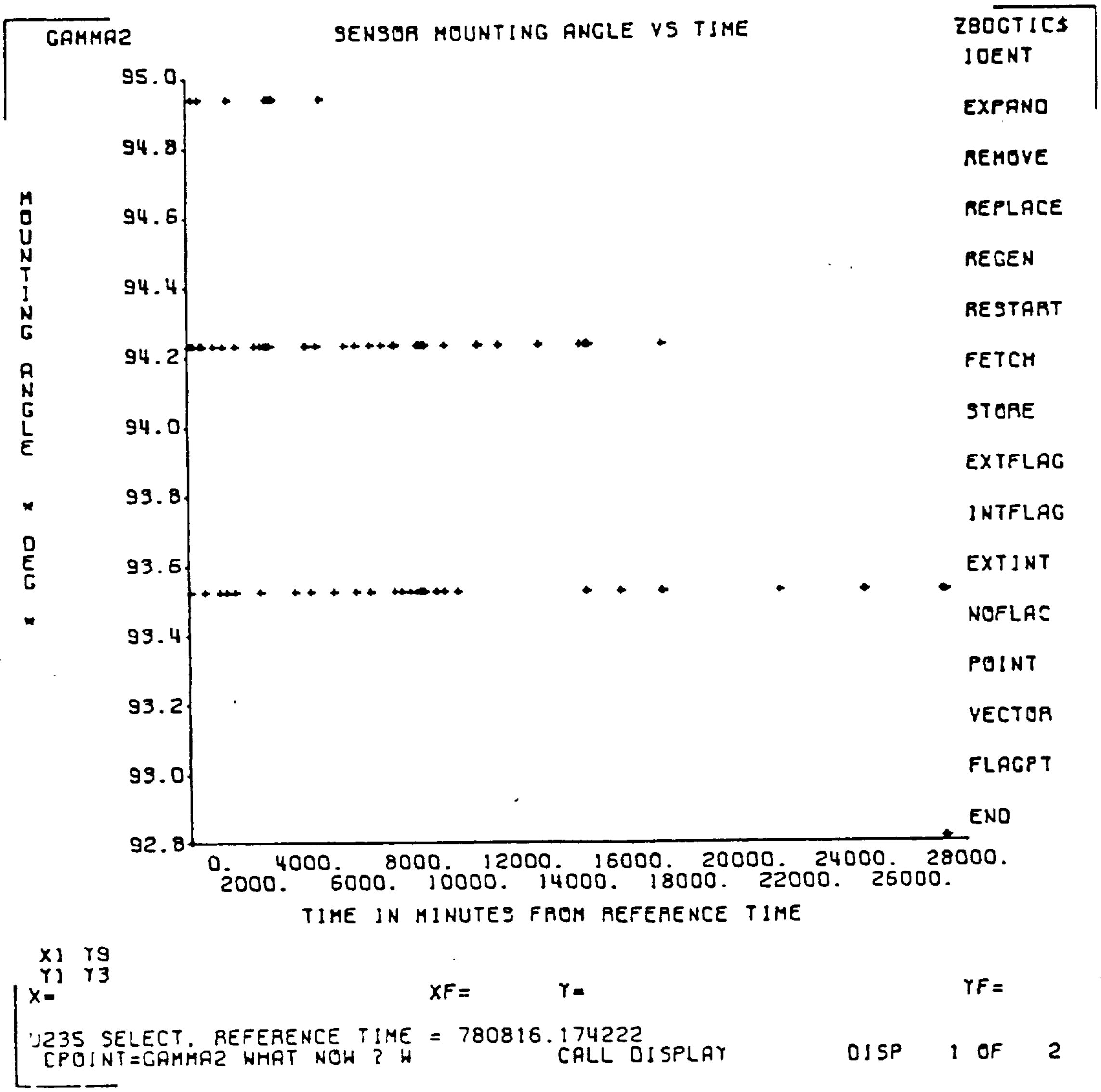

Figure 3-1. PAS Encoder Angle vs Time for Earth Sightings

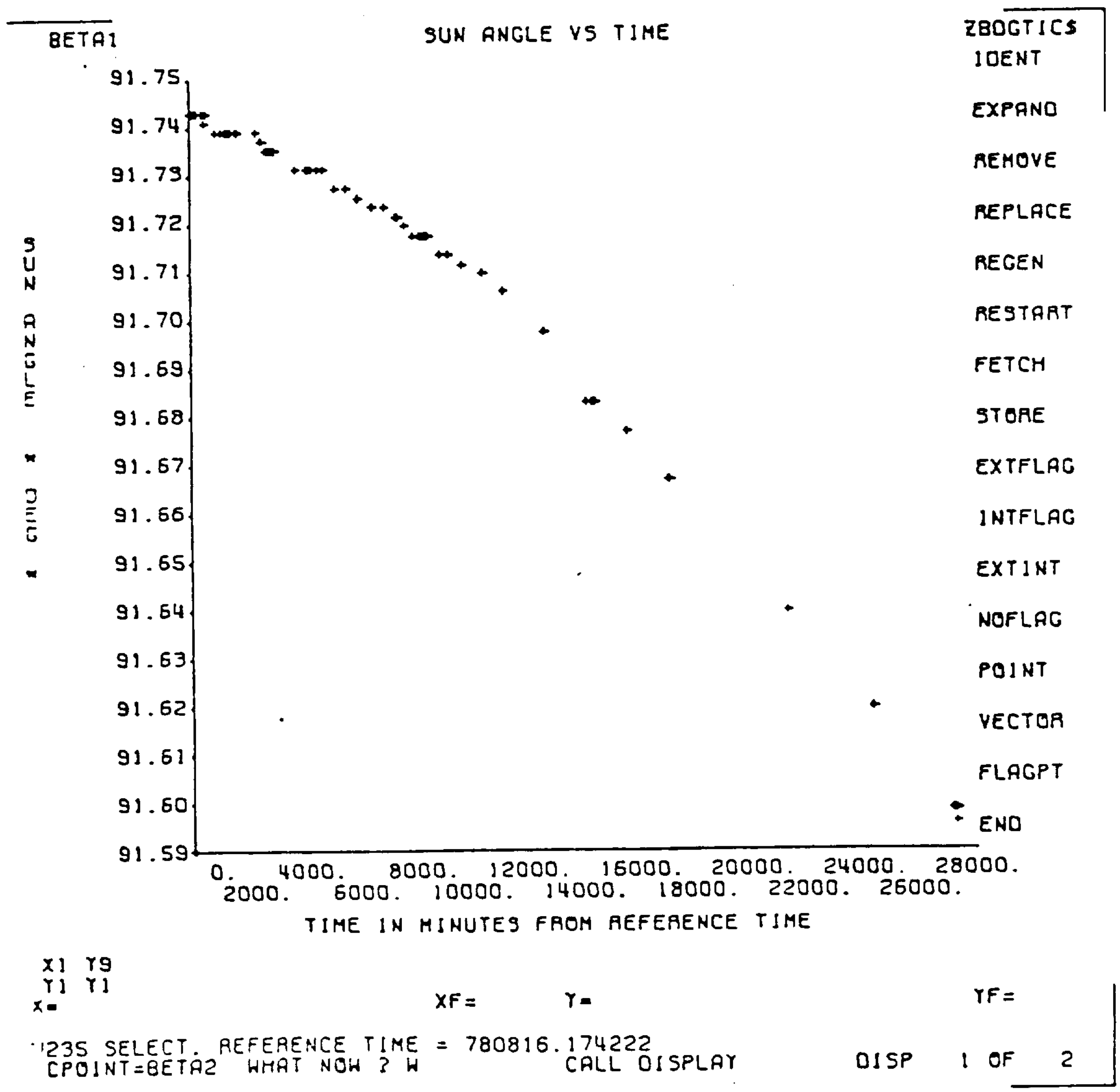

Figure 3-2. Selected Sun Angle Data

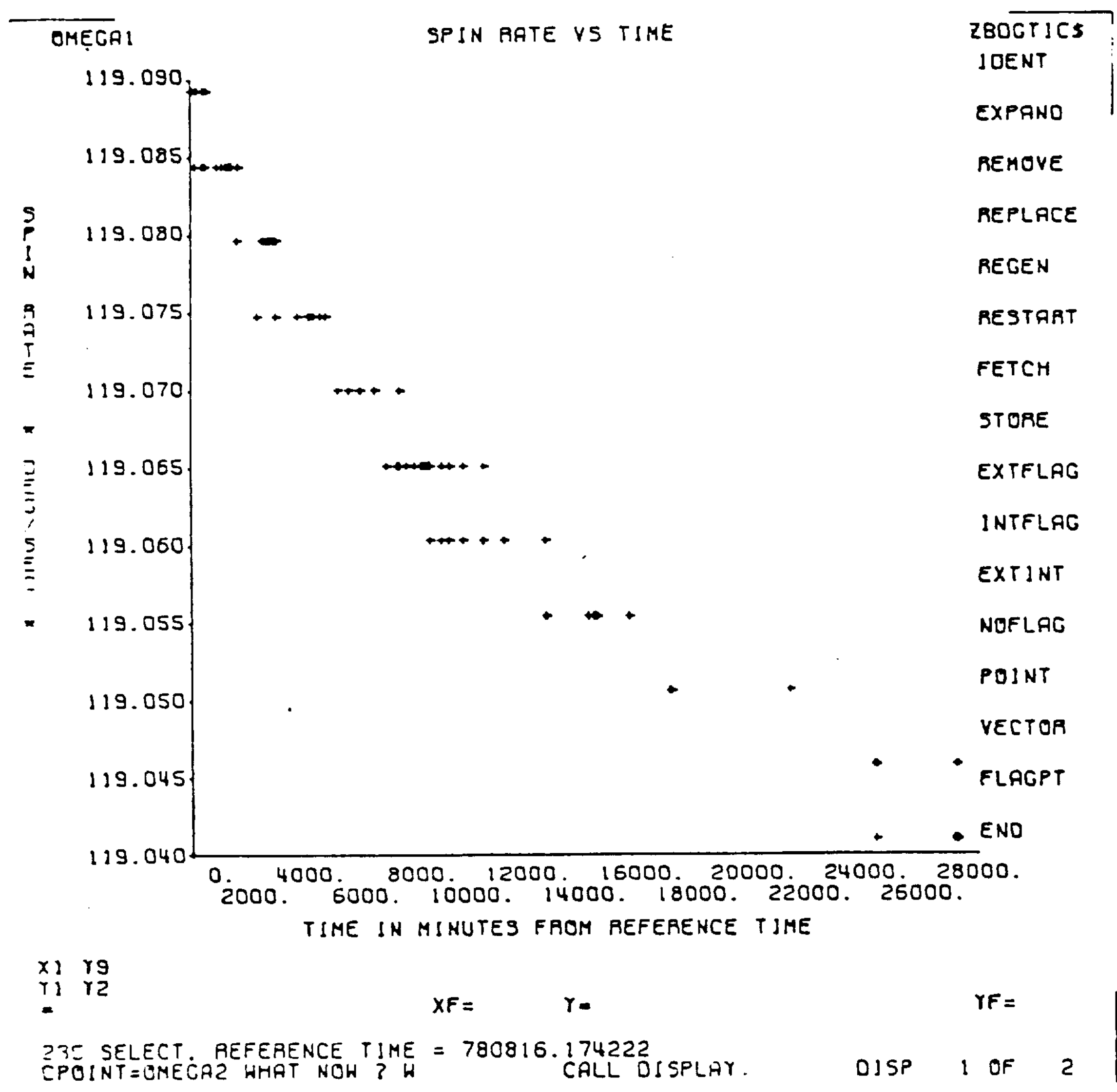

Figure 3-3. Selected Spin Rate Data

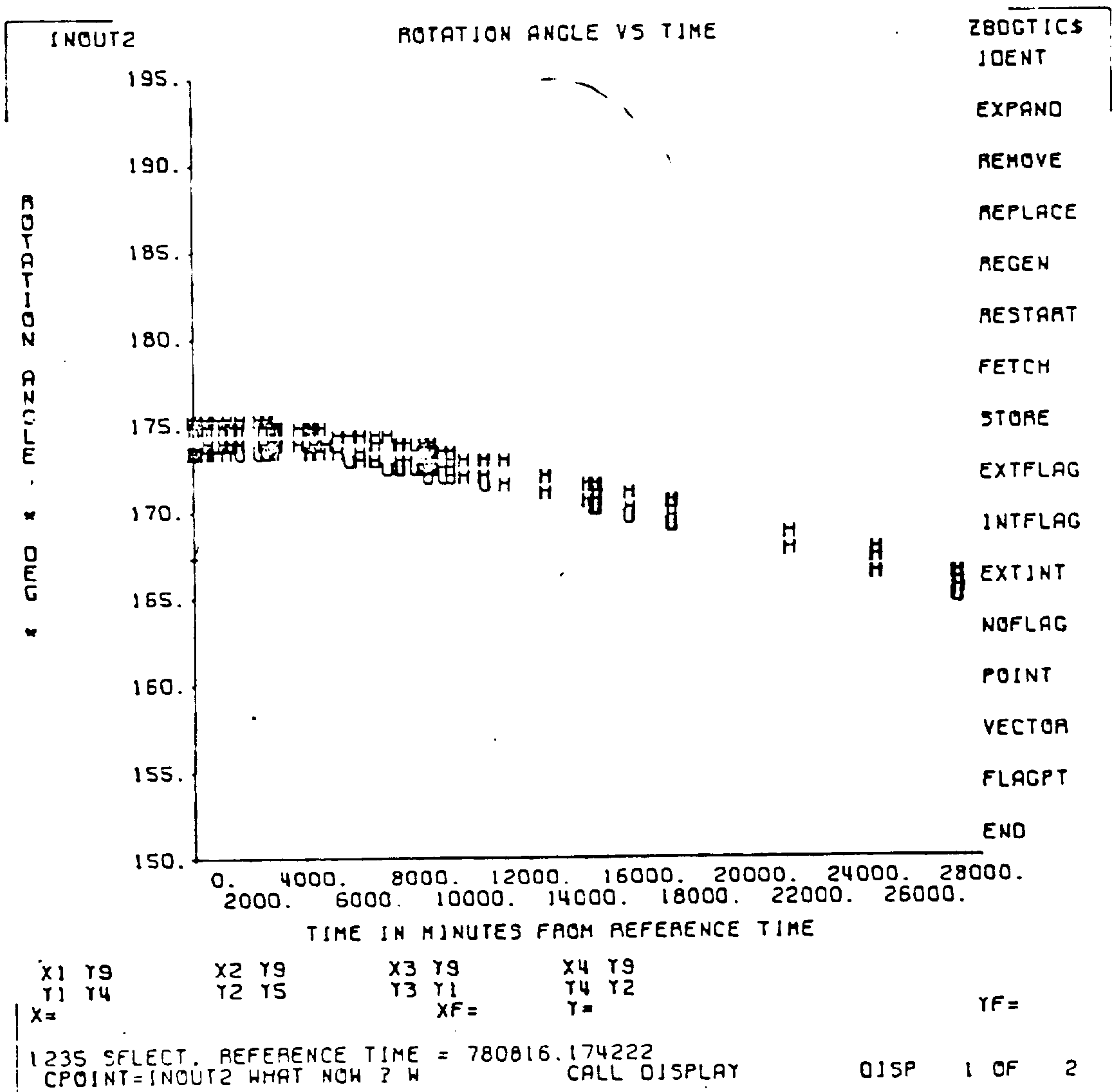

Figure 3-4. Earth Rotation Angles vs Time

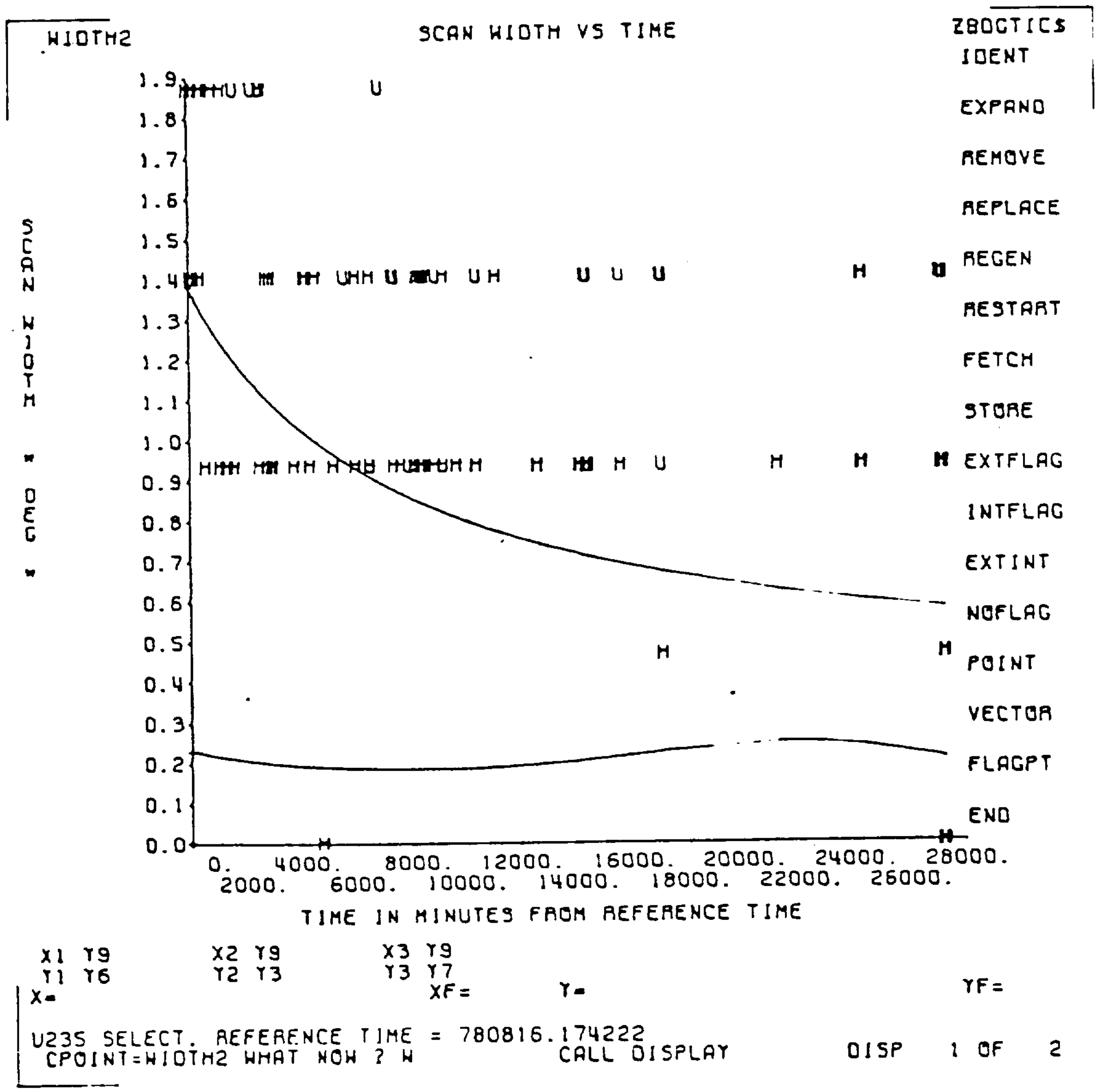

Figure 3-5. Earth Scan Width vs Time

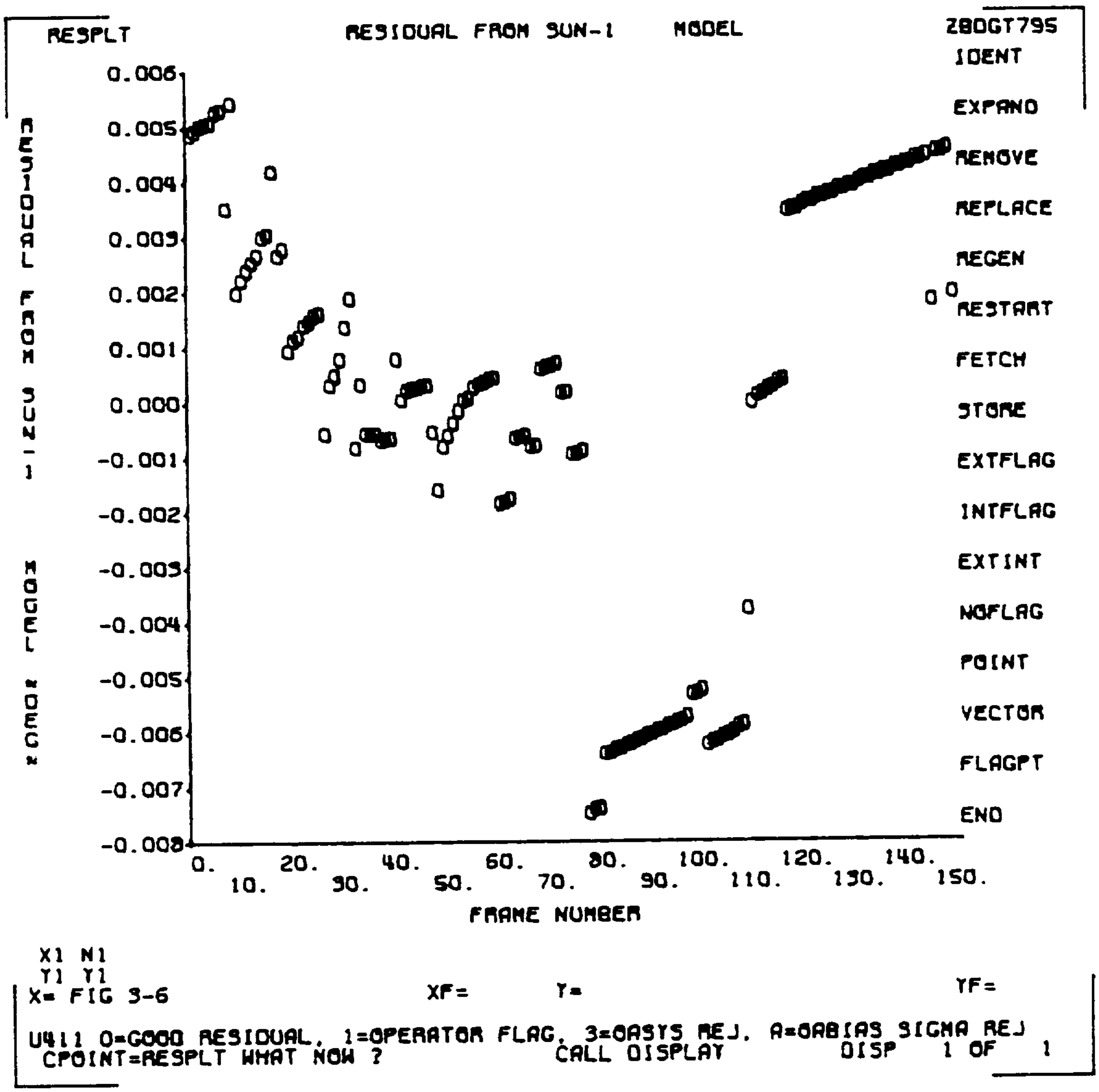

Figure 3-6. OABIAS Residuals From Sun Angle Model for Earth Events

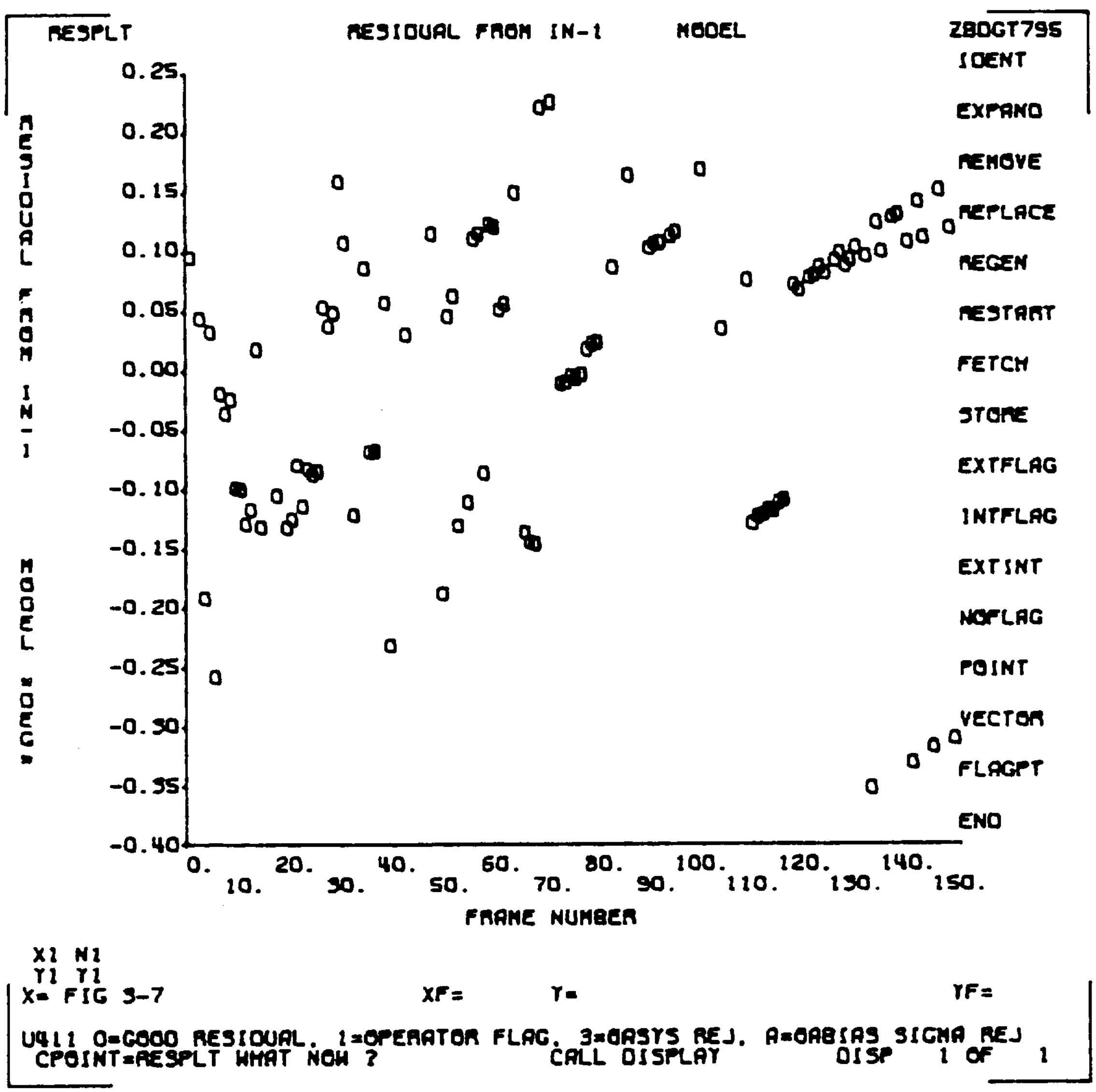

Figure 3-7. OABIAS Residuals From Horizon-In Crossing Model for Earth Events

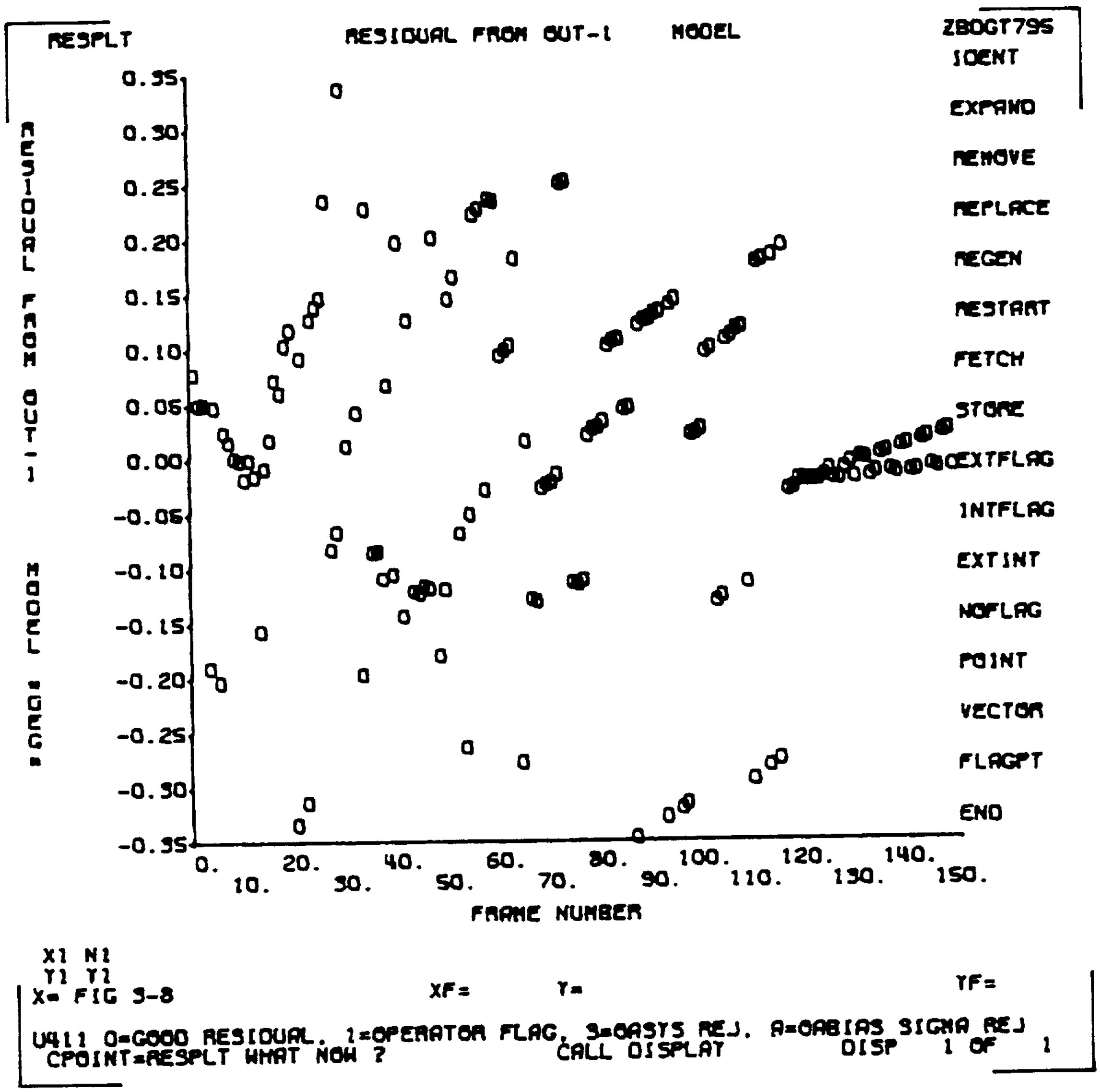

Figure 3-8. OABIAS Residuals From Horizon-Out Crossing Model for Earth Events

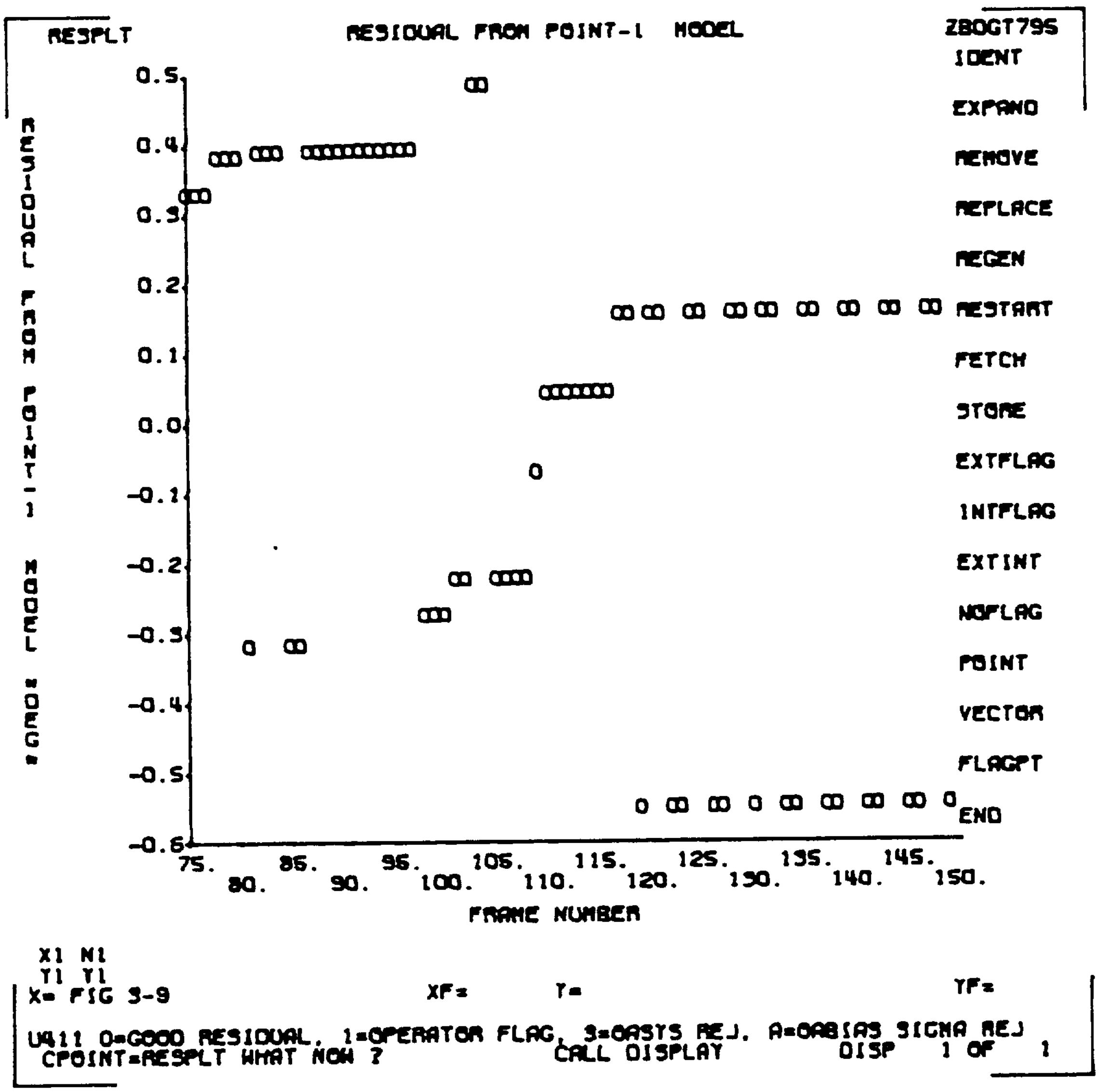

Figure 3-9. OABIAS Residuals From Point Source Model for Earth Events

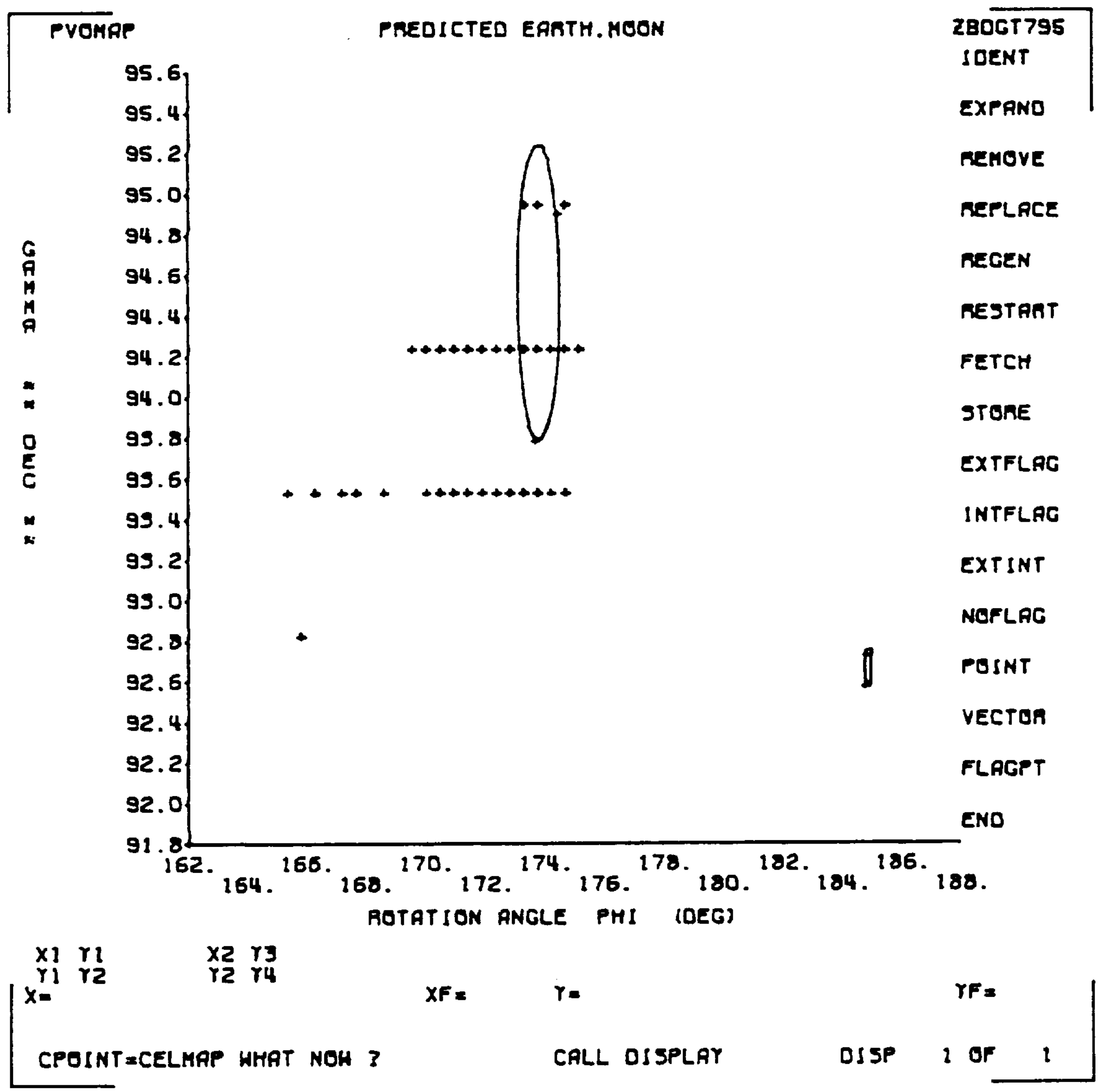

Figure 3-10. Celestial Sphere Plot for Earth OABIAS Solution

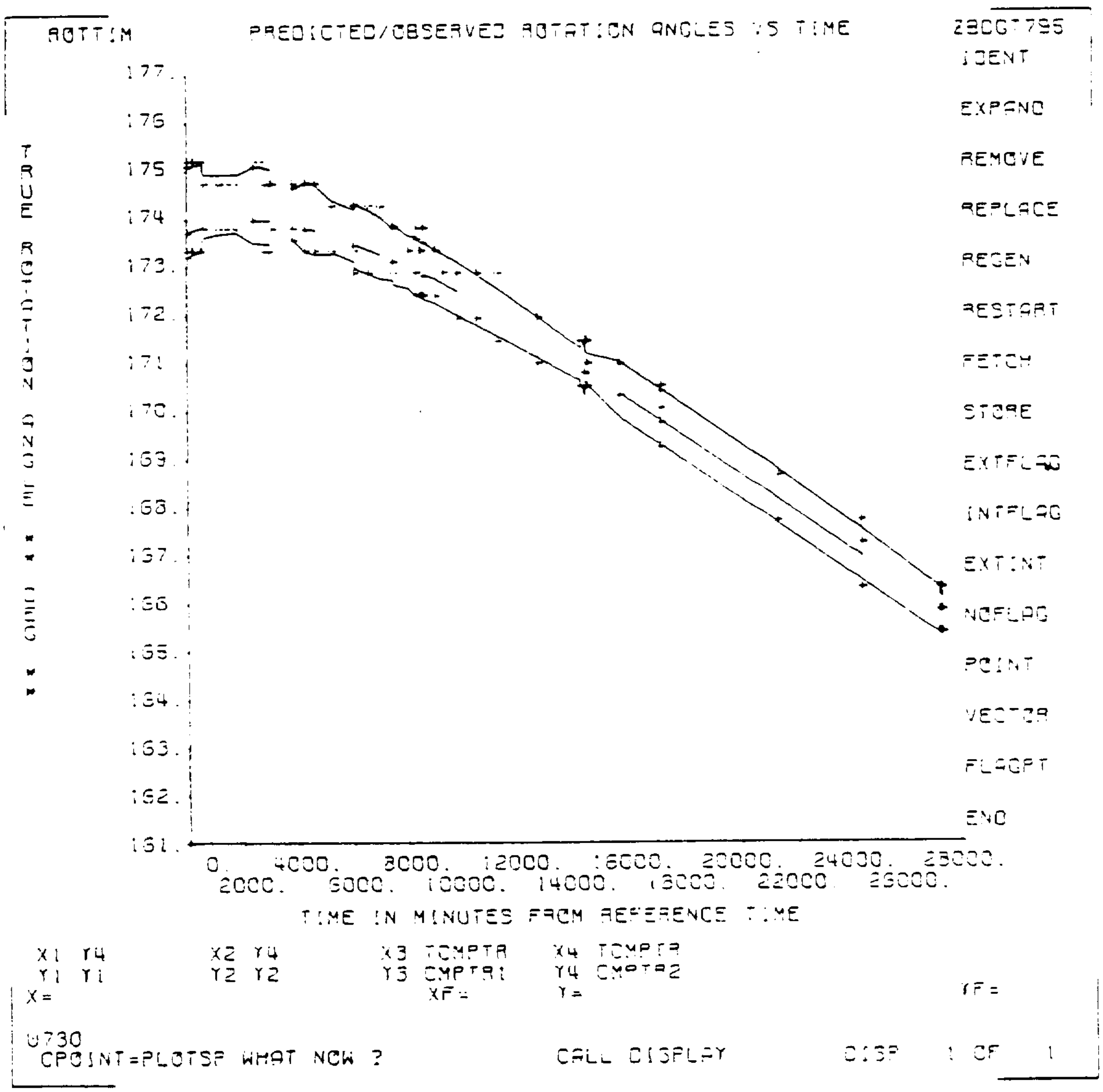

Figure 3-11. Predicted vs Observed Rotation Angles for Earth OABIAS Solutions

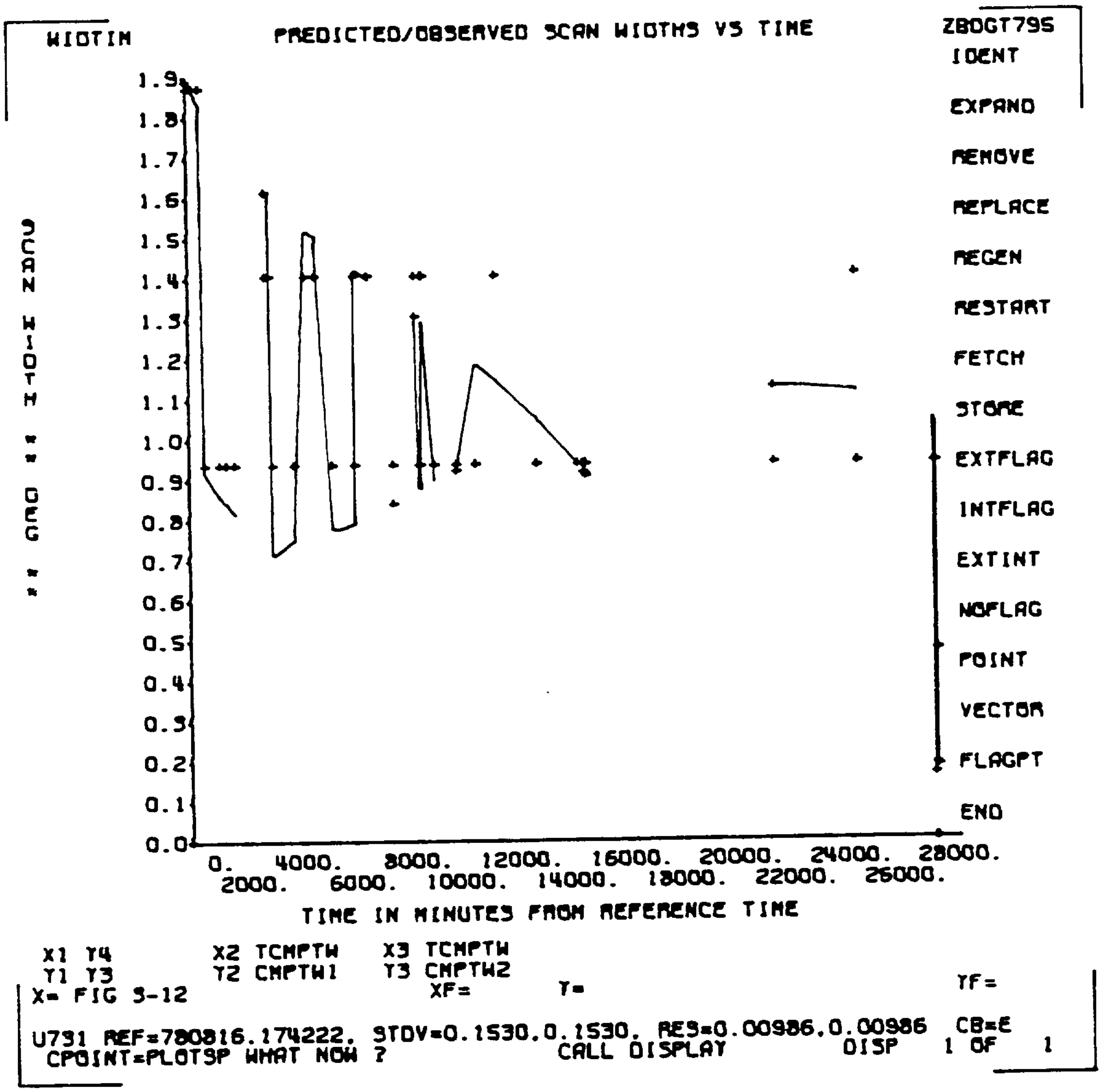

Figure 3-12. Predicted vs Observed Earth Scan Widths for OABIAS Solutions

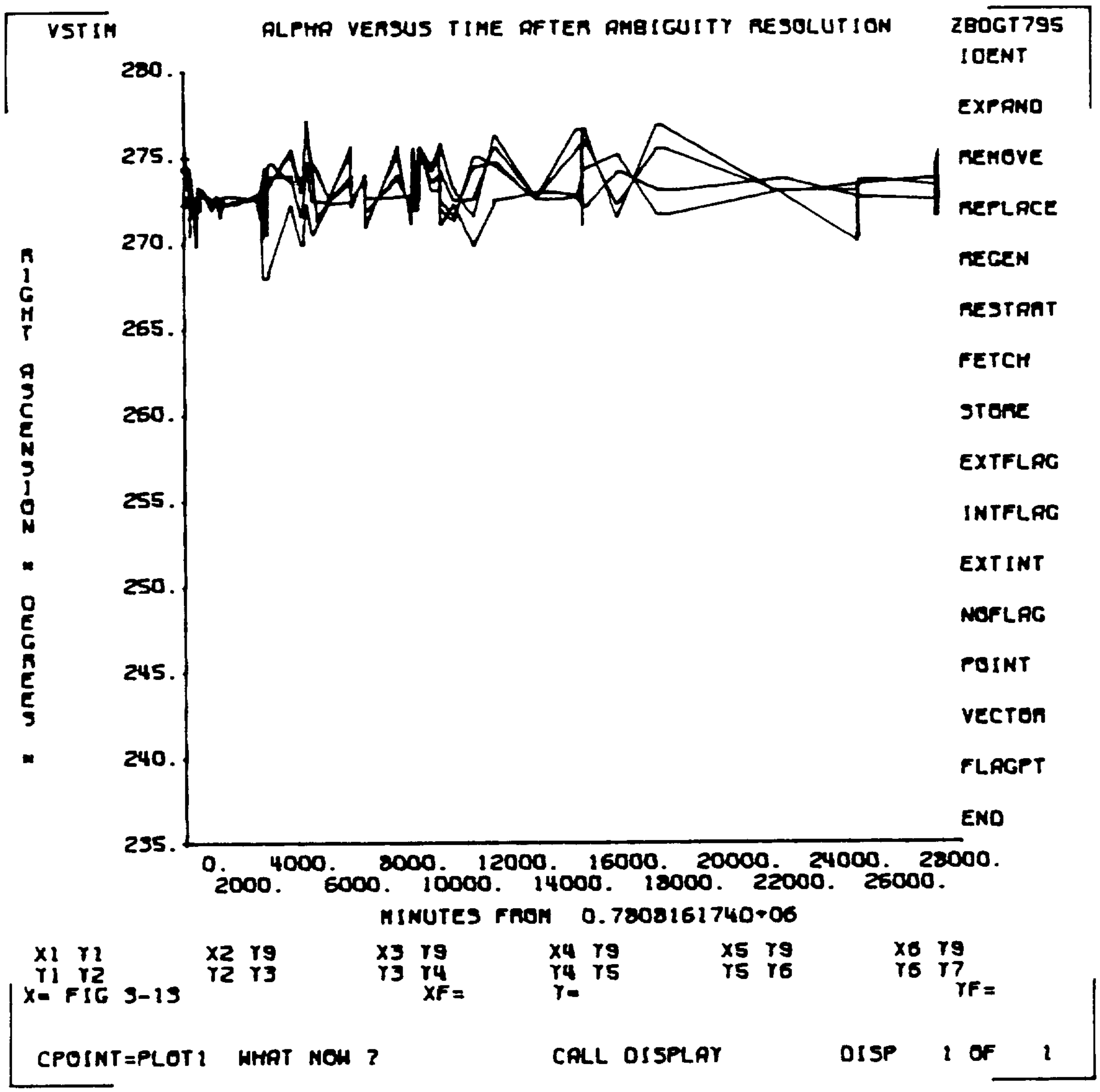

Figure 3-13. Right Ascension vs Time From Deterministic Attitude

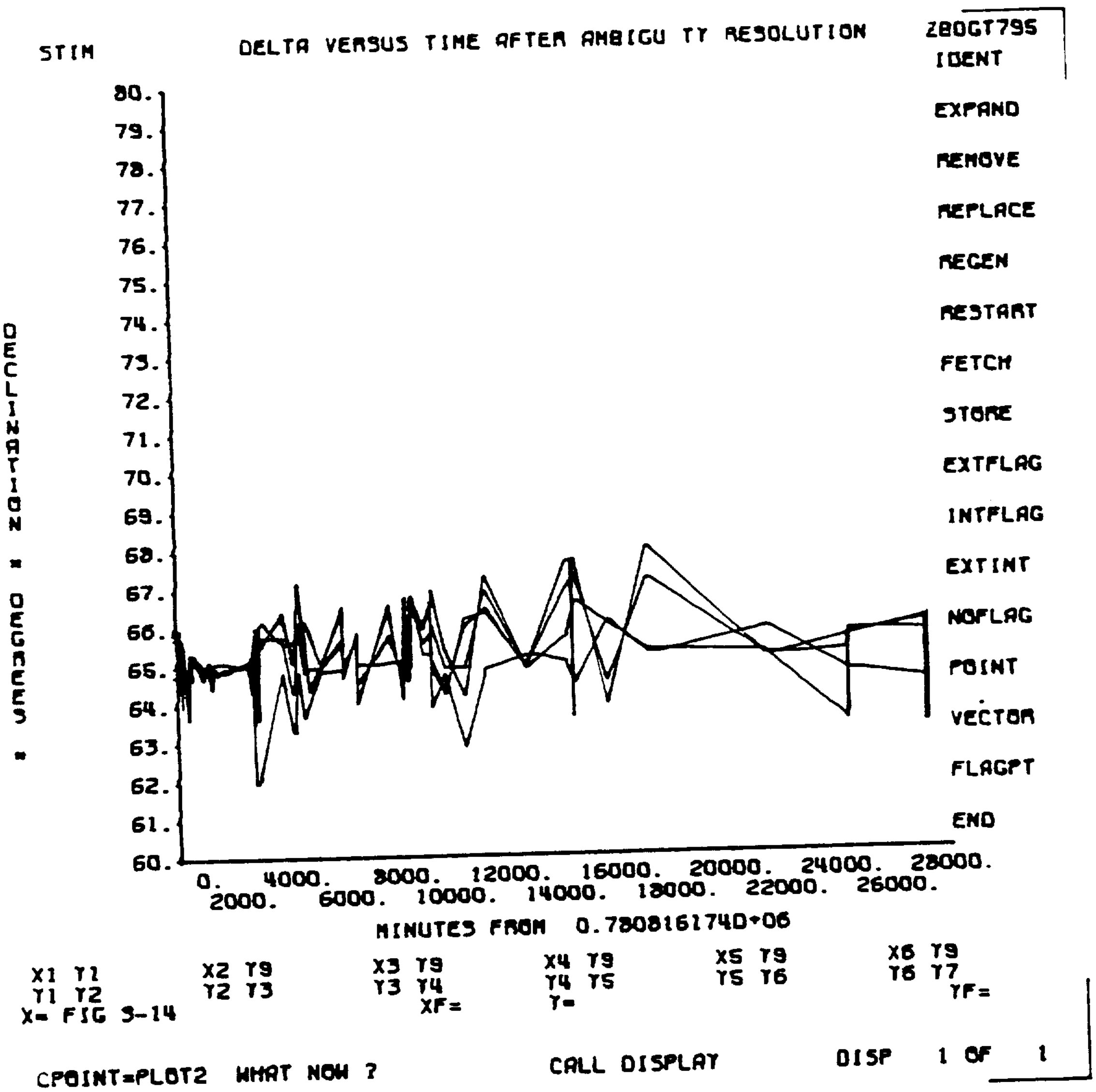

Figure 3-14. Declination vs Time From Deterministic Attitude

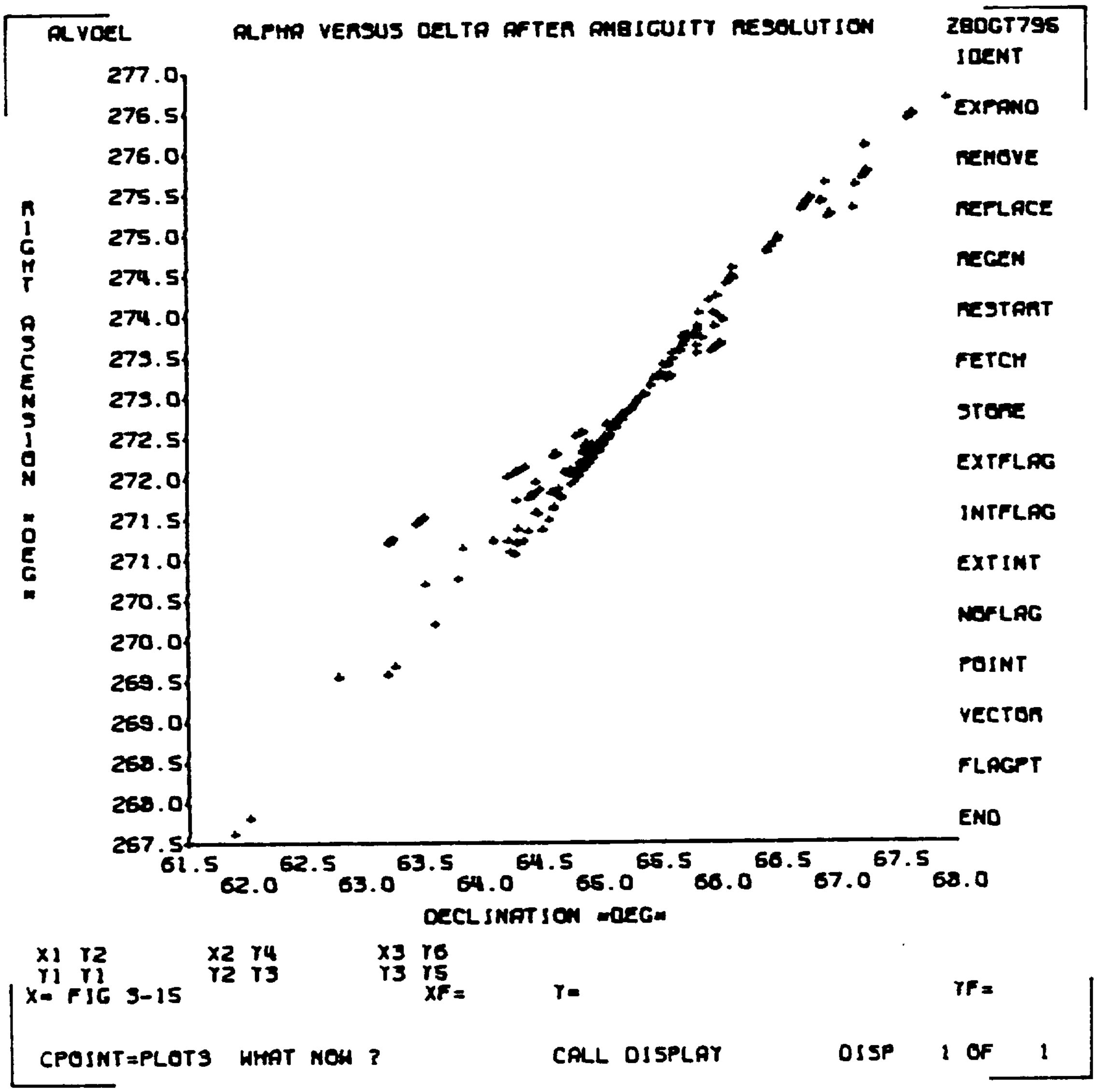

Figure 3-15. Right Ascension vs Declination From Deterministic Attitude

3.2 ATTITUDE DETERMINATION RESULTS FOR THE FSS-ONLY MODE

3.2.1 Software Performance

The performance of the software in the FSS-only mode was excellent. No malfunctions or abends occurred, and the computed attitudes were accurate.

3.2.2 Summary of Attitude Determination Results

Three undisturbed arcs of data, as shown in Table 3-3, fell within the period covered by this report. In Table 3-3, the start and end dates, number of days covered, Sun angle curve fit coefficients, and the reported definitive attitude are given for each arc. Note that a given arc may have been reported in more than one segment, since definitive segments are typically about 1 month long. The second arc of data lasted a total of 75 days and is discussed in detail below.

A detailed analysis of the 75-day arc from September 6 to November 20 was performed to obtain information on the attitude motion of the spacecraft, accuracy and consistency of the attitude solutions, and consistency of the Sun angle measurement between the two Sun sensors. As indicated in Table 3-3, this was reported in three segments. For the purpose of this analysis, however, the arc was processed in one piece. The Sun angle fit for the entire interval was

$$\beta = 89.604^{\circ} + 0.52 \sin(\omega t + 344.47^{\circ}) + 0.43^{\circ} \sin(2\omega t + 187.98^{\circ})$$

where ω is the mean daily motion of the Sun (0.9863 degree/day) and t is the time in days since 780907.032109.

Figure 3-16 is a Sun angle time history during this period. Shown is the daily Sun angle measured by each sensor, the average, and the fit. Data are collected for approximately 30 minutes each day, giving approximately 60 frames which are averaged to obtain the daily point. The attitude history computed from the fit is shown in Figure 3-17.

Table 3-3. Summary of FSS-Only Solutions

ARC	DATE (YYMMDD.HHMM) START / END	NO. OF DAYS	SUN ANGLE CURVE FITTING				DEFINITIVE ATTITUDE	
			MEAN SUN ANGLE (DEG)	AMPLITUDE (DEG)	PHASE (DEG)	EPOCH (YYMMDD.HHMM)	RT ASCENSION (DEG)	DECLINATION (DEG)
1	780814.1030 / 780906.1804	23	90.590	1.21	101.86	780818.2139	273.46	65.41
2	780906.2213 / 781007.0600	31	90.640	1.32	248.37	780907.0321	268.38	66.46
	781007.0600 / 781104.0800	28	91.249	1.91	272.92	781008.0122	268.16	66.66
	781104.0800 / 781120.1834	16	89.604	*	*	780907.0321	267.22	66.87
3	781120.2121 / 781230.0600	42	91.087	0.998	292.339	781121.1048	268.52	67.02
	781230.0600 / 79012.1829	23	91.087	0.998	292.339	781121.1048	267.20**	66.94**

*SECOND HARMONIC FIT GIVEN IN TEXT USED

**THIS ATTITUDE BASED ON PREDICTED EPHEMERIS. DEFINITIVE EPHEMERIS NOT AVAILABLE AT TIME OF WRITING

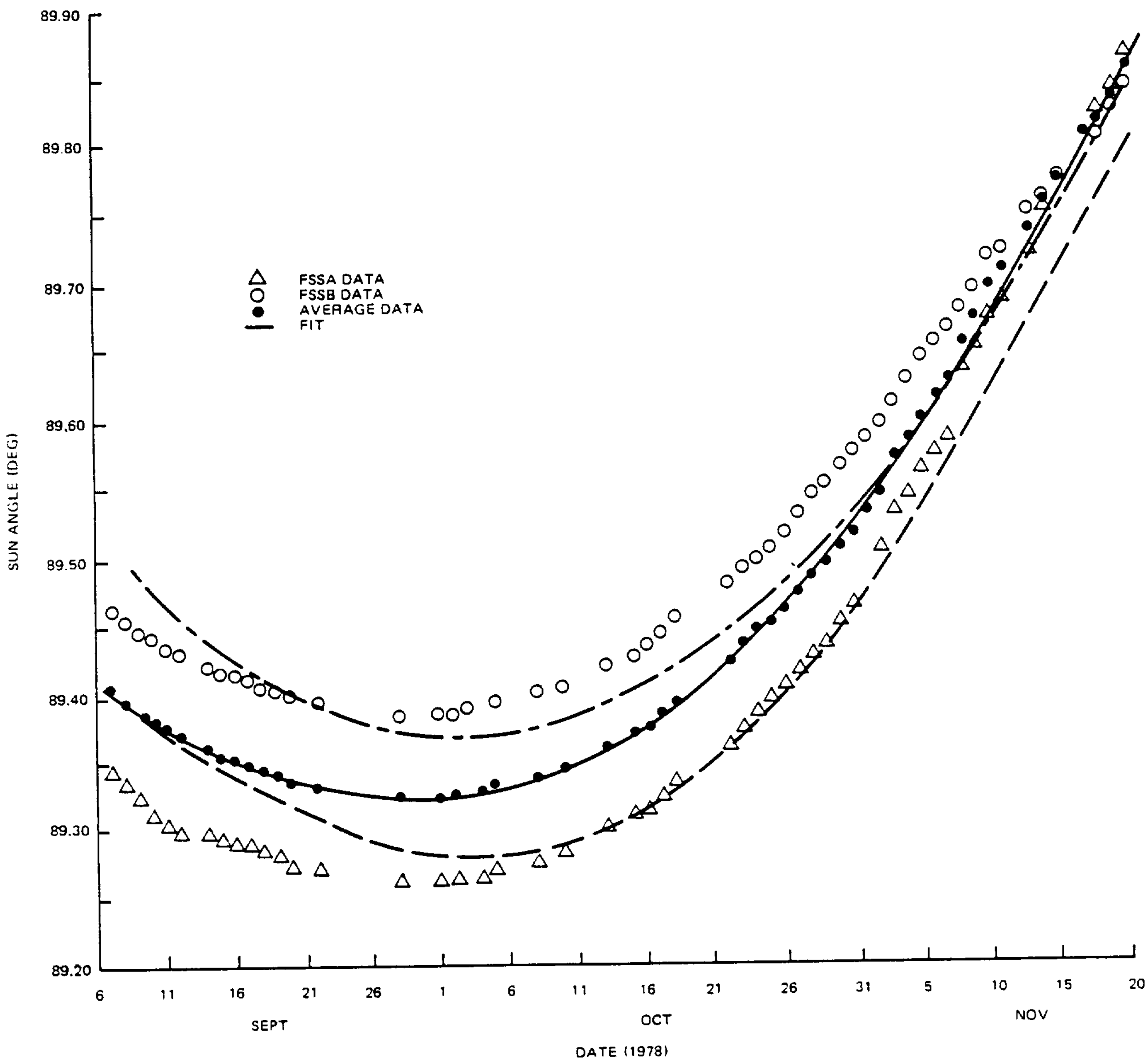

Figure 3-16. Sun Angle History for September 6 to November 20, 1978

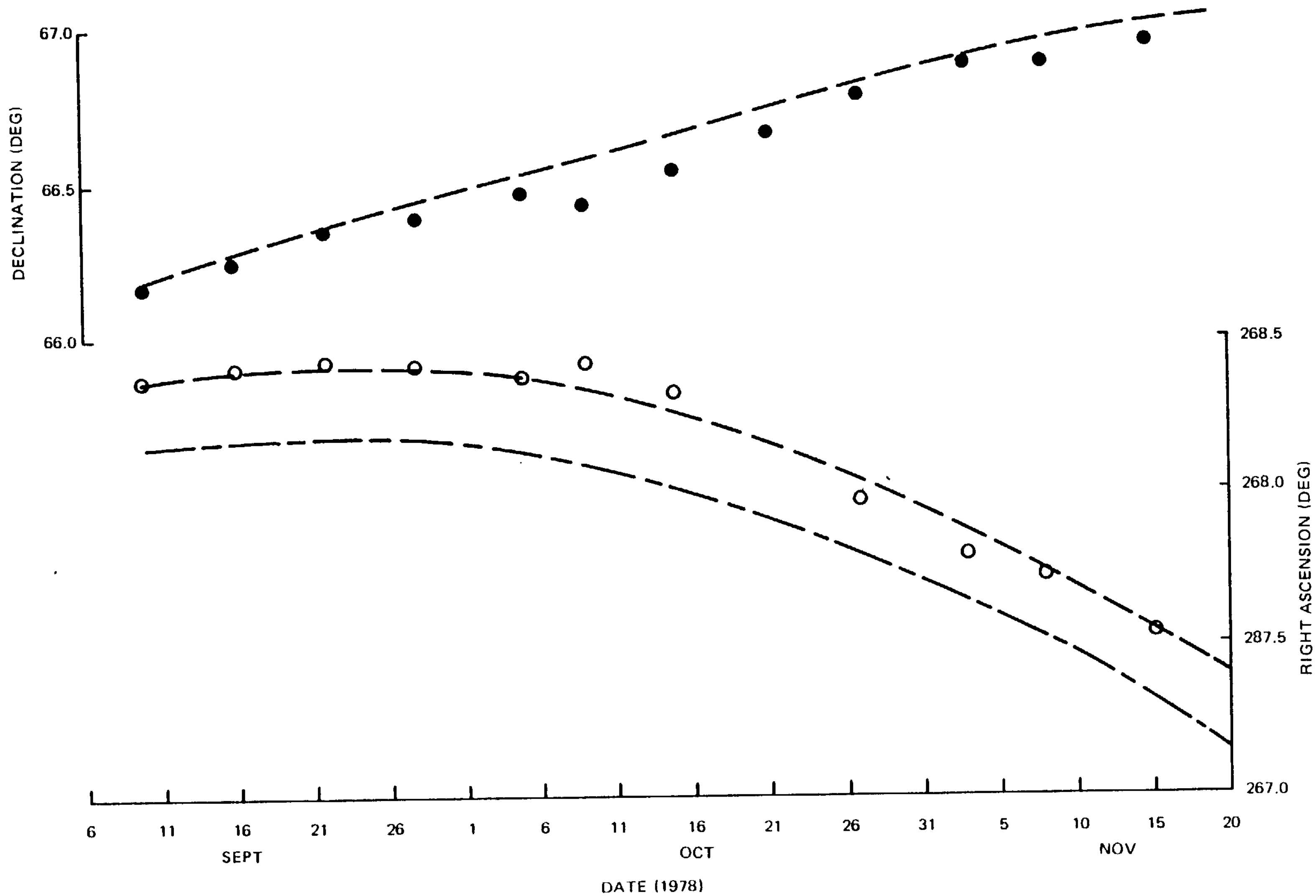

Figure 3-17. Right Ascension and Declination vs Time for September 6 to November 20, 1978

The additional lines on both Figures 3-16 and 3-17 are explained in the subsections below.

3.2.2.1 Attitude Drift

The only significant environmental torque affecting ISEE-3 is that due to solar radiation pressure. The effect of the torque is to produce a motion of the spin axis about a small circle on the celestial sphere (Reference 7); the spin axis will perform one circuit of this small circle in 1 year. The radius, ν, of the small circle was estimated prior to launch to be about 0.5 degree.

The radius may be estimated from attitude solutions as follows. The length, S, of the chord of a small circle of radius ν, which subtends an angle θ, is given by

$$\cos S = 1 - (1 - \cos \theta) \sin^2 \nu$$

so that

$$\nu = \sin^{-1} \left[\frac{1 - \cos S}{1 - \cos \theta} \right]^{1/2}$$

This relation applied to the solutions of Figures 3-17 gives an estimate of υ of about 0.8 degree. This value of υ, along with the initial conditions $\alpha = 268.36$ degrees and $\delta = 66.17$ degrees on 780909.00, was propagated around a small circle of value ν following the Sun. The resulting Sun angle and attitude are shown as dashed lines on Figures 3-16 and 3-17, respectively. The agreement between the measured and predicted attitudes is excellent, but the agreement between the predicted and observed Sun angles initially poor.

To investigate this effect, the initial attitude was perturbed slightly to make the Sun angles agree initially. This shift amounts to about 0.1 degree in arc length and is almost entirely in right ascension. The effect of this shift on the Sun angle history is to improve the agreement at the start of the arc, but to make it worse at the end (dot-dash line in Figure 3-16).

The implications of this perturbation are that either the drift model is oversimplified and/or that the Sun sensors contain some anomalies. In the case of FSSA, a jump was noted in the Sun angle near Nov. 7, 1978 (see Figure 3-16). In any case, the shift of 0.1 degree in attitude is not significant in light of the 1-degree requirement, and the Sun angle shift of 0.1 degree is within the expected accuracy of measurement (when both inherent accuracy and mounting angle biases are considered).

3.2.2.2 Attitude Accuracy

The accuracy required for the mission is ± 1 degree.

The attitude accuracy achieved by the FSS-only technique is discussed in this subsection. A theoretical discussion may be found in Reference 1 and is summarized below.

The attitude using FSS data only is found by combining the Sun angle, β, with the Sun angle time rate of change, $\dot{\beta}$. The geometry is illustrated in Figure 3-18. The attitude is defined by the angles β_o and Θ. The Sun angle, β_o, is measured directly and is the value at the time the attitude is to be computed, while the angle Θ is computed from $\dot{\beta}$ as described in Reference 7. The coordinate system of Figure 3-18 is a body system (called the SCR system) in which the X-axis points from the spacecraft to the Sun at the time the attitude is to be computed; the Y-axis is in the direction normal to the X-axis and normal to a vector pointing in the direction of the North Ecliptic Pole (NEP) in the sense of NEP $\times$ $\hat{X}$; and the Z-axis completes a right-handed coordinate system. The SCR system is noninertial, and so a transformation into an inertial attitude, defined by right ascension and declination, must be performed. This transformation requires the spacecraft ephemeris.

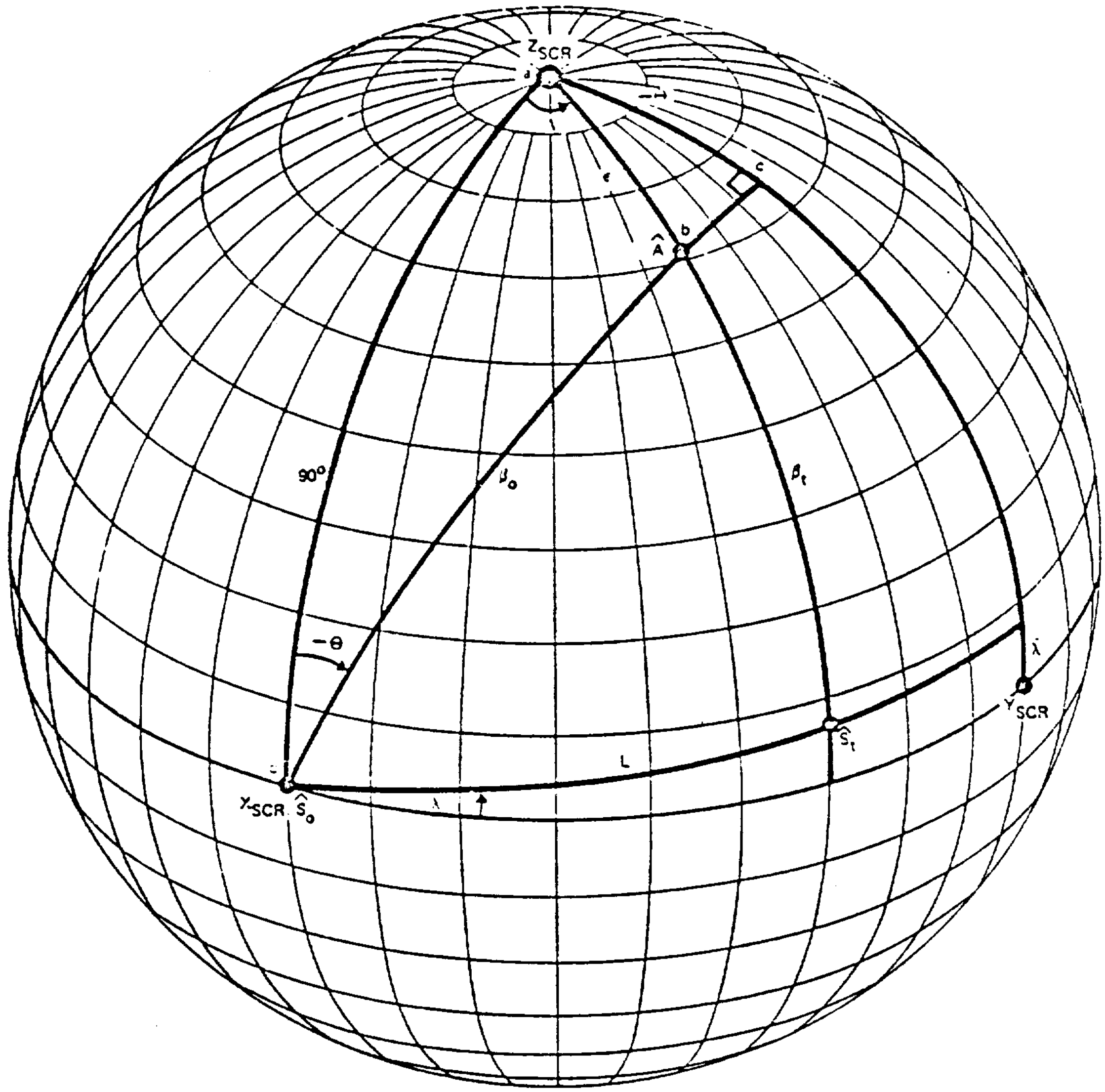

Figure 3-18. FSS-Only Attitude Determination Geometry

It is apparent from the foregoing discussion that the factors affecting the attitude uncertainty are the uncertainty in β , the uncertainty in $\dot{\beta}$, and the uncertainty in the spacecraft ephemeris. Dynamic imbalance also must be considered. This is taken to be 0.2 degree, which is the maximum offset between the geometrical spin axis and the principal axis (the measured prelaunch offset was much less than 0.2 degree).

The inherent accuracy of the FSS is ±0.05 degree in the range $87^{\circ} \leq \beta \leq 93^{\circ}$. Any mounting angle bias is specified to be less than 0.05 degree in magnitude. Prelaunch analysis indicated that this bias cannot be determined, and so it is treated as an uncertainty. The uncertainty in β therefore was taken to be ± 0.1 degree.

The uncertainty in the Sun angle rate of change, $\dot{\beta}$, is determine by the resolution, $\delta\beta_R$, of the FSS and by the change in calibration factors as a function of Sun angle. The resolution of the FSS is ± 0.004 degree, and the maximum prelaunch error in Sun angle per unit Sun angle change, $\delta\beta/D\beta$, is 0.2 degree/degree (Reference 1). The net uncertainty in $\dot{\beta}$, $\delta\dot{\beta}$, is given by

$$\delta\dot{\beta} = \frac{\delta\dot{\beta}}{D\beta}\,\dot{\beta} + 2\frac{\delta\beta_R}{\Delta t}$$

where Δt is the time interval over which $\dot{\beta}$ is determined. The maximum $\dot{\beta}$ is about 0.02 deg/day for attitude near the North Ecliptic Pole ($/\Theta/ \leq 1^{\circ}$).

The uncertainty in the attitude in the SCR system is taken as the root sum square of the uncertainty in Θ , and in β , and the dynamic imbalance.

The attitude uncertainty in an inertial system is obtained by adding in an estimate of the ephemeris uncertainty. A worst-case estimate can be obtained by neglecting the halo orbit ephemeris and assuming that the spacecraft stays at the liberation point. In this case, it may be shown that the maximum error in β is about 0.05 degree, and the maximum error in β is about 0.003 degree/ day, which corresponds to about ± 0.2 degree uncertainty in Θ.

Table 3-4 shows the attitude uncertainty $|\delta A|$ computed as outlined above as a function of Δt.

It is clear from the above discussion that attitude undertainties on an order of $\pm$ 0.6 degree are expected from this technique with 10 days of data or more. Verification that this accuracy was achieved requires comparison with an independent technique. There are three possibilities for comparison:

1. Sun-only solutions using cone intersections
2. Sun-only solutions using a differential corrector
3. Sun/Earth solutions using PAS data

In the first two techniques, the attitude is assumed constant during the pass used to compute the attitude. In the third, some bias determination is required which means in practice that the attitude must be assumed constant over a typical definitive arc.

Extensive analysis of the PAS solutions was performed on the arc from August 14 to September 6; thus, a comparison of these three techniques with the FSS-only method, using β and $\dot{\beta}$, was made for this interval. The results are given in Table 3-5. The maximum difference is less than 0.25 degree.

Table 3-4. Theoretical Attitude Determination Uncertainty for FSS-Only Method

Δt (day)	$\delta\dot{\beta}$ (deg/day)	$\delta\Theta$ (deg)	$\lvert\delta A\rvert$ (deg)
1	0.0120	0.69	0.98
2	0.0080	0.46	0.76
5	0.0056	0.32	0.64
10	0.0048	0.28	0.61
15	0.0045	0.26	0.59
20	0.0044	0.25	0.58
30	0.0043	0.24	0.58
60	0.0041	0.24	0.58

Table 3-5. Difference (Degrees) Between FSS-Only and Other Techniques

	FSS Only	FSS Cones	FSS/PAS
FSS Cones	0.17	-	-
FSS/PAS	0.23	0.07	-
FSS Diff Corr	0.24	0.08	0.01

SECTION 4 - ATTITUDE CONTROL RESULTS

A summary of the attitude and spin maneuvers performed through January 12, 1979 is given in Table 4-1, and a summary of the results is given in Table 4-2. In Table 4-1, the predicted values have been adjusted to take into account factors such as moments of inertia and initial conditions which were not necessarily known at the time the maneuvers were performed.

4.1 SPIN MANEUVERS

A total of five spin maneuvers has been performed. Examination of Table 4-1 indicates that spin-up maneuvers have averaged $\approx$ 5 percent cold, while spin-down maneuvers have averaged $\approx$ 4 percent cold. There is no indication of significant attitude motion as a result of spin maneuvers performed with a proper couple.

The first spin maneuver was performed blindly by firing the nominal 3 pulses. An estimate of spin rate was not obtained due to PAS commanding problems (see Section 2.2.1). A subsequent analysis of the FSS data indicated that the initial spin rate was about 6.96 rpm, and therefore the achieved final spin rate of 9.12 rpm is reasonable (the initial spin rate was expected to be 5.6 rpm).

The second spin maneuver again was performed with the nominal commands and the results were as expected.

Spin maneuvers 3 and 4 were both spin-down maneuvers, number 3 following antenna deployments and number 4 following an attitude maneuver. During the performance of spin maneuver 3, the number of pulses required was seriously underestimated because of uncertainty as to the mass properties following the antenna deployments. The nominal maneuver called for 8 pulses, but 15 actually were required when the proper mass properties were obtained. The agreement between predicted and observed change was excellent. The commands for spin maneuvers 4 and 5 were computed by hand, based on performance

Table 4-1. Summary of Maneuver Commands

MANEUVER	PREDICTED STATE (INITIAL / FINAL)				ACHIEVED STATE (INITIAL / FINAL)				ARC LENGTH MOTION (DEG)		HEADING ANGLE (DEG)		SPIN RATE CHANGE (RPM)	
	SPIN RATE (RPM)	SUN ANGLE (DEG)	ATTITUDE ALPHA (DEG)	ATTITUDE DELTA (DEG)	SPIN RATE (RPM)	SUN ANGLE (DEG)	ATTITUDE ALPHA (DEG)	ATTITUDE DELTA (DEG)	PREDICTED	ACHIEVED	PREDICTED	ACHIEVED	PREDICTED	ACHIEVED
SPIN NO. 1	6.96 / 9.44				6.96 / 9.12								+2.48	+2.16
ATTITUDE NO. 1 LEG 1	9.12 / 9.19	82.64 / 91.93	54.21 / 352.73	21.73 / 70.60	9.12 / 9.24	83.2 / 91.1	53.6 / 355.0	22.0 / 71.2	60.2	59.3	98.69	97.6	+.07	+.12
LEG 2	9.19 / 9.26	91.94 / 96.22	352.73 / 277.73	70.60 / 61.12	9.24 / 9.32	91.1 / 94.8	355.0 / 281.0	71.2 / 64.4	29.8	26.9	98.26	97.9	+.07	+.08
SPIN NO. 2	9.30 / 37.97				9.32 / 38.68								+28.65	+29.36
ATTITUDE NO. 3	38.89 / 38.89	93.70 / 91.48	281.40 / 272.40	66.00 / 66.44	38.89 / 38.91	93.71 / 91.72	28.14 / 273.08	66.0 / 65.30	3.65	3.5	53.62	56.6	0	+.02
SPIN NO. 4	20.98 / 19.86				20.98 / 19.85								–1.12	–1.13
ATTITUDE NO. 4	20.18 / 20.18	91.53 / 89.73	273.00 / 269.26	65.49 / 66.68	20.18 / 20.19	≈91.3 / 89.41	* / 268.3	* / 66.4	1.93	*	339.13	*	0	+.01
SPIN NO. 4	20.19 / 19.73				20.19 / 19.77								–.46	–0.42
ATTITUDE NO. 5	19.92 / 19.92	89.75 / 89.97	267.7 / 270.0	66.85 / 66.56	19.92 / 19.92	≈89.8 / 91.71	* / 269.28	* / 66.87	1.06	*	102.91	*	0	0
SPIN NO. 5	19.92 / 19.79				19.92 / 19.83								–0.13	–.09
ATTITUDE NO. 6	19.83 / 19.83	90.84 / 90.15	267.02 / 269.53	66.95 / 66.62	19.83 / 19.83	90.84 / 90.19	* / 269.7	* / 66.7	1.04		48.35			

*NOT DETERMINED - SEE TEXT

Table 4-2. Summary of Attitude and Spin Maneuver Results

MANEUVER TYPE	NUMBER	START TIME / STOP TIME (YYMMDD HHMM)	ESTIMATED FUEL USED (lb)	HPS 1 TANK PRESSURE (PSIA) INITIAL / FINAL	HPS 1 TANK WEIGHT (lb) INITIAL / FINAL	HPS 2 TANK PRESSURE (PSIA) INITIAL / FINAL	HPS 2 TANK WEIGHT (lb) INITIAL / FINAL	COMMAND JETS USED	COMMAND NO PULSES	COMMAND PULSE WIDTH (DEG)	COMMAND SECTOR	REMARKS
SPIN	1	780812.1657	0.11	568.8 / 568.2	24.41 / 24.38	568.8 / 568.2	24.41 / 24.38	A + B	3	45	0	
ATTITUDE	1/2	780812.1838 / 780812.1910	1.67			568.2 / 552.6	24.38 / 23.96	N	117	45	208	
ATTITUDE	2/2	780812.1919 / 780812.2000	1.64			552.6 / 539.1	23.96 / 23.55	F	116	45	719	
SPIN	2	780812.2030	1.16	568.2 / 564.0	24.38 / 24.95	539.1 / 537.6	23.55 / 23.46	A + B	110	45	0	
ATTITUDE	2											CANCELLED
ATTITUDE	3	780814.1010	0.58			537.6 / 533.0	23.46 / 23.32	N + E	95	45	79	
SPIN	3	780815.1550	0.09			533.0 / 530.5	23.32 / 23.30	G + H	15	22.5	0	
ATTITUDE	4	780906.2157	0.29	497.5 / 494.9	22.06 / 21.99			N + E	26	45	891	
SPIN	4	780906.2240	0.05	494.9 / 494.0	21.99 / 21.98			G + H	6	22.5	0	
ATTITUDE	5	781120.2120	0.18			461 / 460	20.21 / 20.17	N + E	15	45.0	219	
SPIN	5	781120.2140	0.05			460 / 460	20.17 / 20.17	G + H	2	22.5	0	
ATTITUDE	6	790112.1829	0.15					N + E	28	22.5	100	

during spin maneuver number 3 and the predicted mass properties and tank pressures. Excellent results were obtained.

4.2 ATTITUDE MANEUVERS

Attitude maneuvers were performed with jets N and F, singly, and with N and E as a couple.

Attitude maneuver number 1 was performed using N on the first leg and F on the second leg in order to calibrate these jets for use in subsequent orbit maneuvers. The predicted and observed Sun angle time history during this maneuver is shown in Figure 4-1. Predicted values are shown for both the original targeting run and for the post launch reconstruction (Reference 5).

Table 4-1 indicates that the first leg of this maneuver was essentially nominal, while the second leg was 8 percent cold. Subsequent use of these jets in orbit maneuver number 1 indicated that both jets were probably 5 percent cold. In any case, the relative calibration factor was incorrect, since during orbit maneuver 1, the attitude moved in the direction opposite to that predicted (Reference 5). The calibration factors were modified for the second orbit maneuver, and fairly good agreement was obtained between the predicted and observed Sun angle motion (Reference 5).

Attitude maneuver number 2 was canceled since the final attitude from attitude maneuver number 1 was close enough to that required for the first orbit maneuver.

Attitude maneuver number 3 was performed using the nominal commands, and the results indicate that N + E is about 4 percent cold, and 3 degrees off in heading angle. The same combination was used for attitude maneuvers numbers 4 and 5, but no calibration was possible because of the short time interval between the attitude maneuver and the end of orbit maneuver number 2. The Sun/Earth geometry limits the solution accuracy to about 12 degrees, and the Moon was too dim to be visible to the PAS.

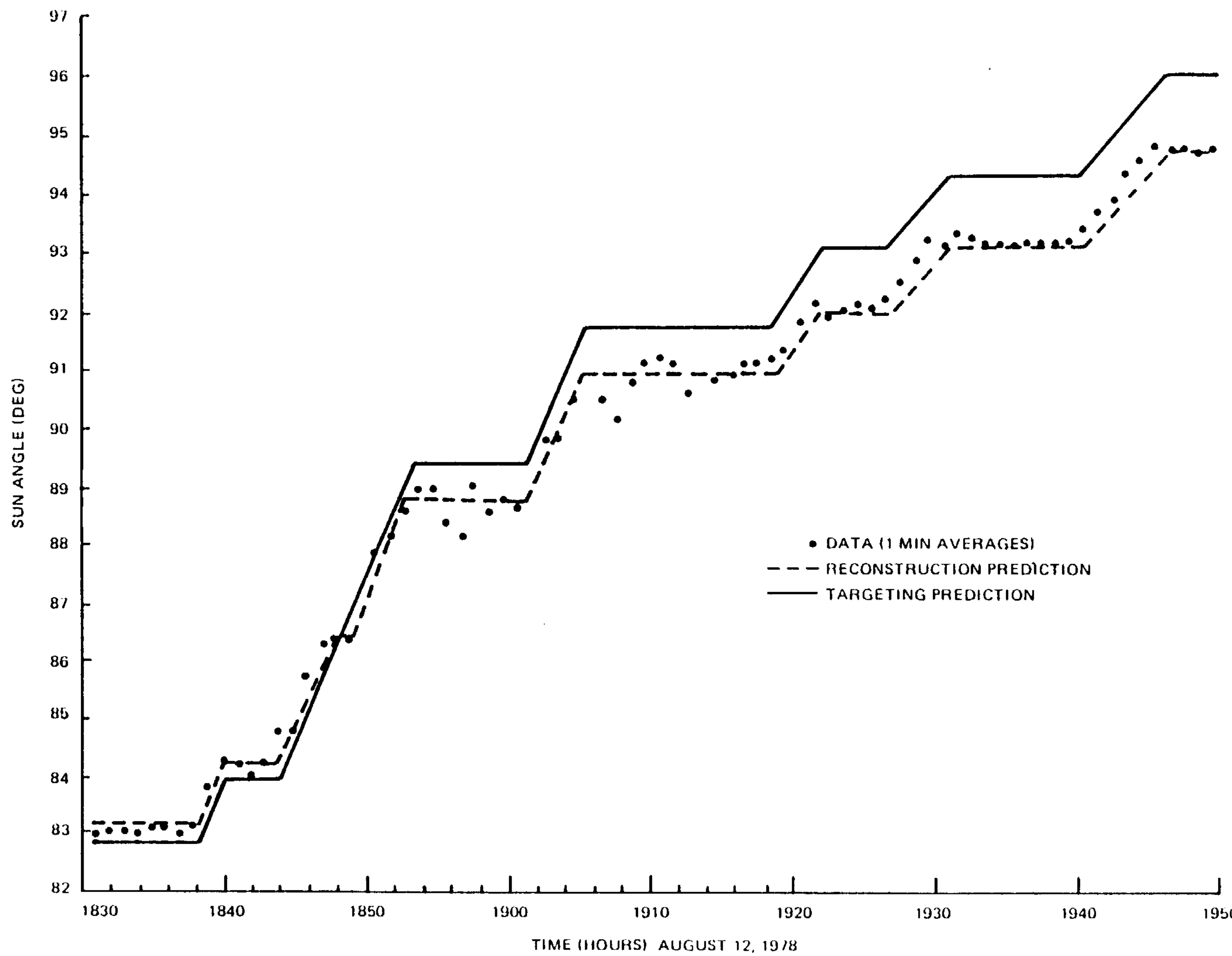

Figure 4-1. Sun Angle History During Attitude Maneuver Number 1

4.3 SUMMARY AND CONCLUSIONS

The performance of the control system appears to be within 5 percent of nominal, well within the $\pm$ 10 percent expected prior to launch. No malfunctions of the control system occurred, and its excellent performance contributed significantly to the overall success of the mission.

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